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Rationally Recommended Illumination Levels

By H. C. WESTON, O.B.E. (*Fellow*)

Summary

Some of the visual objectives for which different levels of illumination are, or may be, recommended are considered and mention is made of the kind of experimental data available for the development of illumination prescription systems. Such experimental data underlie the recent Russian and American recommendations which are discussed briefly. It is taken as always desirable that lighting installations in regularly occupied interiors should provide sufficient illumination to create an agreeable environmental or ambient luminance, irrespective of the specific visual tasks occupants may be required to do: hence, what illumination may be recommended reasonably for securing this basic amenity luminance in places of work is considered. The existing British analytic method of finding basic values of illumination for various definite visual tasks is examined and a modification is proposed to simplify practical use of the method. In view of this, a new definition of the visual performance criterion is proposed and a general, although moderate, increase in recommended levels of illumination is likely to be consistent with this.

(1) Introduction

Standards of illumination cannot be recommended rationally for different purposes unless these purposes are defined in suitable terms. A purpose so loosely described as 'inspecting cloth for stains' is too indefinite: we need more particulars, such as whether the cloth is light or dark in colour, how small are the stains that should be seen and how slight is the discolouration that should be detected. Particulars of this kind can be got in numerical terms which indicate the degrees of visual capacities needed to perform the task and, since visual capacities vary with illumination in known manner, these particulars are helpful in specifying the illumination.

Any visual jobs for which it is desired to lay down standards of visual capacity or of illumination, or both, must be evaluated from the job specification—if this is available in suitable detail—or it must be done by field observation, analysis and measurement. The process of visual job analysis is not considered in detail in this paper but it is stressed here that the evaluation to which it leads, or a suitable evaluation arrived at by some alternative procedure, is essential if any moderately finely graded scale of illumination levels is to be fitted authentically to a wide diversity of tasks.

Such a serial order of illumination levels has characterized every prescription system that has been applied hitherto. But it is not indispensable; illumination might be prescribed very simply—as indiscriminately and as lavishly as Nature sometimes does it.

The manuscript of this paper was received on February 19, 1960. The paper was presented at a meeting of the Society held in Harrogate on May 16, 1960.

(2) General Criteria

Levels or standards of illumination may be, and have been, recommended on the basis of various criteria, each of which has reference to some visual objective. The following examples may be considered:

(*a*) adequacy for preventing occupational 'eyestrain', unnatural deterioration of sight, and the risk of accidental injury due to bad visibility;
(*b*) adequacy for maximum visual capacity;
(*c*) adequacy for creating an agreeable luminous environment;
(*d*) adequacy for a standard degree of 'suprathreshold' visibility and an associated standard visual capacity;
(*e*) adequacy for *different* 'satisfactory' levels of visual performance, each standard being applicable to a particular range in the gamut of visual tasks.

Levels of illumination recommended as mandatory minima in factories were first chosen in this country chiefly to satisfy criterion (*a*), and this criterion is still the primary one for protective minima. It is generally assumed to be an insufficiently exacting criterion for levels recommended as good practice. Criterion (*b*) is unnecessarily exacting. If it were adopted no code would be necessary—merely a single value. The evidence is that this value would have to exceed 1,000 lm/ft². While it could be maintained that such a criterion is rational from a

functional standpoint it is scarcely so practically and economically. Nevertheless, what may be termed a 'unitary and massive' solution of the illumination prescription problem is not entirely without advocates.

The third criterion is one of those adopted by the British I.E.S. and, also, it has become one of the criteria for the statutory minimum illumination in factory working areas. By itself, however, it does not lead to recommended levels which are functionally desirable for the most difficult practical visual tasks. It is a criterion which takes account of the most general psychological effects of environmental luminance, apart from the requirements for performance of particularly exacting work. Criterion (*d*) is one that has long had its advocates in the U.S.A., and it is explicity the criterion of the latest method developed in that country for recommending levels of illumination. Some of its effects are mentioned in the next section of this paper.

The fifth criterion is one of those adopted by the British I.E.S. and, implicitly, by similar bodies in those other countries whose recommendations are in good agreement with our own. It is also the criterion for the new Soviet illumination 'norms'. There is reason for believing that, eventually, it will be reverted to in the U.S.A., although this would not necessarily involve complete agreement with British recommendations.

The experimental data available for consideration in formulating illumination recommendations with these criteria in view are still substantially those relating to the limits—under special conditions—of certain visual capacities such as, acuity, contrast sensitivity, colour discrimination and speed of perception. These data do not yield recommendable values of illumination directly, but they are certainly valuable. They have been reviewed from time to time by various writers. Unfortunately, data obtained from field investigations planned and undertaken specifically to ascertain optimum or near optimum levels for practical visual tasks are still not very numerous, but some of the most reliable of them have been obtained in this country. There are very serious difficulties in making field investigations and getting unequivocal results from them yet, of course, there is no disguising the fact that demonstration of what is to be gained by using this illumination rather than that in 'real' situations is more convincing to most people than a case reasoned from adequately controlled 'lab' situations.

Between these two sources of relevant data lies another which is the partially simulated 'real' situation: the author has used this source in addition to field investigations. The data for the prescription method proposed later, in section 5, were obtained from self-paced visual tasks typical of many 'real' tasks and these were performed under conditions not too dissimilar to those of everyday work situations.

(3) Recent New Recommendations

In 1959 a complete revision of their previously recommended levels of illumination was undertaken by the American I.E.S. in view of a new method of specification propounded by H. R. Blackwell as an outcome of his laboratory researches.[1] The new levels recommended are higher than those they supersede by an average factor of about three. All the new levels have been chosen by 'technical committee groups of lighting experts after consideration of all valid illumination research findings, known lighting principles, and vast experience'.[2] Thus, the newly recommended levels are not claimed to be derived directly and solely by the Blackwell method, but the preliminary publication in 1958 of this method and of the experimental data underlying it, provided the immediate stimulus for recommending substantial increases. In passing, it may be remarked that substantial increases could have been proposed at any time within the past fifteen years with as much —or as little—justification from available British and other data.

On January 1, 1959, new norms for electric lighting came into operation in the U.S.S.R.[3] They apply in new or reconstructed industrial buildings, residential accommodation and public buildings, and also to open spaces. Minimum values of illumination at industrial working locations are specified for a series of task categories each member of which is defined primarily in terms of size and contrast of detail to be resolved, as in the familiar British code. The minimum working illumination specified varies from 10 dekalux (i.e. approximately 10 lm/ft²) for rough work (apparent size of detail not smaller than 1°), irrespective of the reflectivity and contrast of the work-objects, to 300 dekalux for very fine work where the angular subtense of the detail is 1 min. or less and the contrast is low with a dark background. So-called 'superhigh' levels of illumination are not prescribed because, although they ensure finer discrimination, their prolonged use is said to induce fatigue of the central nervous system and, consequently, to reduce working capacity.[4]

An unusual feature is the prescription of two scales of minima—one for fluorescent and another for tungsten lighting. Except at the lower end of the range, the values prescribed for tungsten lighting are half the values prescribed for fluorescent lighting. The reason for this is not given, but it is stated that fluorescent lighting should for preference be used where visibility has to be particularly good, as for precision work involving considerable visual strain. This suggests that the prescribed minimum values

are related to the lighting load, although Soviet physiologists and illuminating engineers claim to have found a difference in the levels of visual perception and productivity in conditions of equal brightness according as they are got by tungsten or fluorescent lighting. This has not been demonstrated in other countries.

The criterion for the norms is not stated but may be inferred from a simultaneously published paper by Shaikevich.[4] This author points out that the classification of visual tasks adopted—which, as previously mentioned, is similar to that in the British code—is based on certain laws governing the functioning of the eye, and that different norms are adopted in the various classes and sub-classes in order to produce, so far as possible, equal visibilities. Here we meet with an objective which was in the mind of Beuttell[5] who expressed it as 'equal facility of vision'. But he believed, quite rightly, that as between the most difficult visual tasks and the simplest or basic tasks equal facility of vision or equal visibility is impracticable. In fact, Shaikevich finds that the Soviet prescribed illumination levels are far from giving equal visibility. He has suggested limiting values of contrast for the different size classes such that a better approximation to 'equal visibility' may be obtained when the appropriate levels of illumination are used but, even so, these levels do not equalize the visibility of all grades of tasks nor do they yield equal rates of task performance. The absolute rates of performance are lower for the more difficult tasks which are done with the higher illuminations than they are for the easier tasks which are done efficiently with the lower illuminations. This finding is similar to that of the present author[6] and of Ferree and Rand.[7]

By accepting the fact that equal visibility or equal performance are unrealistic criteria—requiring a levelling-down system using handicapping levels of illumination for relatively easy tasks—the Soviet norms are accommodated within a fairly narrow range whose limits are in the ratio of 30: 1. The prescribed values are, however, mandatory minima and so are not directly comparable with the recommended but not obligatory values in the British and American codes. Nevertheless, as minima they must be regarded as high but, according to Shaikevich, higher values up to 1,000 dekalux allow only a slight lowering of the contrast limits he suggests for different classes of size if the rate of performance is to remain unaffected. As the present author has shown,[8] where size is very small and contrast very poor magnification is more effective than 'superhigh' illumination.

Although the impracticability of a criterion defined as a common level of visibility or of performance for widely differing visual tasks has been shown quite clearly, such a criterion has been adopted —at least nominally—for the latest U.S.A. recommended values of illumination in so far as their claim to be 'scientific' rests upon their consistency with computations by the currently recommended version of the Blackwell method. This criterion is stated to be tripartite but, in fact, two of its components are dependent on the third. The stated components are (*i*) a so-called standard level of visual capacity sufficient for the assimilation of at least five items of information per second (5 APS),* at (*ii*) a standard accuracy level of 99 per cent, with (*iii*) a supra-threshold visibility factor of 15. Component (*iii*) is the critical one. If it is secured, by the appropriate choice of luminance level, components (*i*) and (*ii*) are said to ensue. The adoption of this criterion results in restrictively low prescriptions of illumination for easy tasks and impracticably high prescriptions for the most difficult tasks. In fact, for tasks 'measured' by the Blackwell Task Evaluator the levels of illumination range from 0·6 lm/ft^2 for reading 12-point type to more than 10,000 lm/ft^2 for seeing white chalk on tan cloth or grey stitching on grey silk.

Contrast sensitivity data, on which the structure of the Blackwell method is erected, have been obtained by a number of investigators. The various sets of data are not in complete agreement but they have not all been obtained by the same experimental techniques. Blackwell's own set were got from a small number of young observers and, for the purpose of his system he has extrapolated to the extent of one log unit above the highest luminance he used. Doubt as to the suitability of this kind of 'threshold' data as a foundation for a working illumination prescription system was the reason for obtaining the present author's more directly relevant performance data.[5] Others (e.g. ref. [9]) also have questioned the suitability of what are usually understood by 'threshold' measurements as a starting point from which to evolve practical recommendations. However, Wittig[10] has deduced illumination values from Schumacher's contrast sensitivity data which correspond well with those derived by Kruithof and Kruithof[11] from the present author's visual performance data. And Fry[12] by comparing these latter data with the contrast threshold data of Conner and Ganoung[13] finds a constancy of relationship which he thinks supports the principle on which the validity of Blackwell's system depends.

However this may be, the end result which emerges from the Blackwell system is critically dependent upon a factor—the so-called supra-threshold or field factor—which has been used to 'bridge the gap' be-

* This is the interpretation put upon a demonstrated capacity to assimilate at least one item of information exposed for ¼th. second.

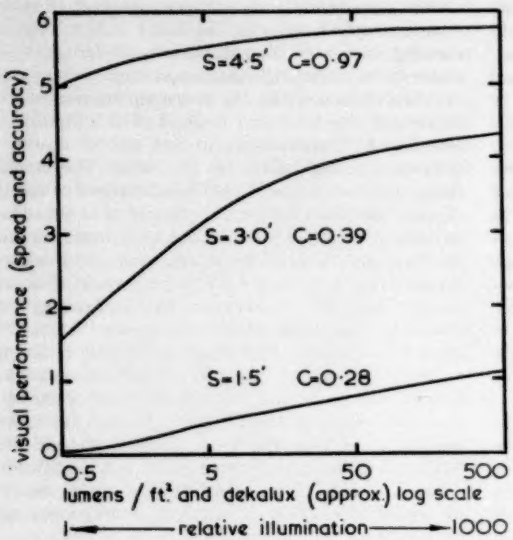
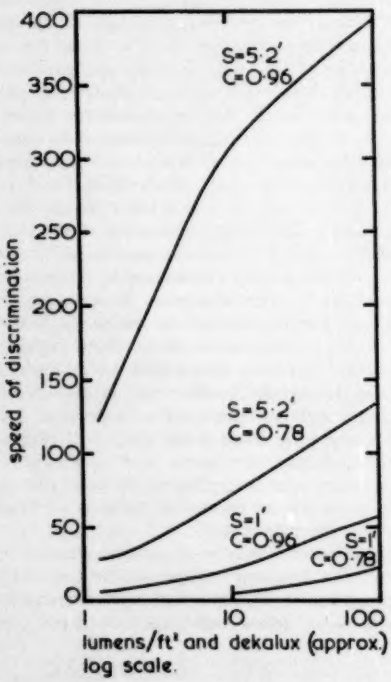
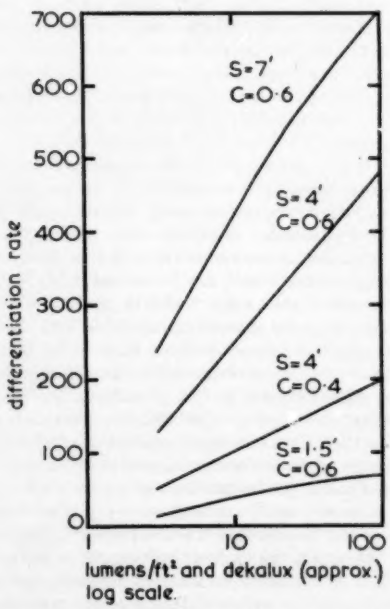


Fig. 1 (left). The relation between visual performance and illumination for three standard visual tasks each involving perception of detail of different size and contrast. The ratio of sizes is only 3:1 and that of the contrasts only about 3·5:1, yet it is evident that the performance of the most difficult tasks under the maximum illumination used is far lower than the performance of the easiest of the tasks under an illumination only 1/1000th of the maximum. (Weston, ref. [6].)

Fig. 2 (below left). The relation between illumination and the speed of discrimination for two sizes of detail and two degrees of contrast, using test-object similar to that for Fig. 1 but with controlled exposure time. Again it is evident that the performance of the most difficult of the tasks under the maximum illumination used is much lower than the performance of the easiest task under a much lower illumination. (Ferree and Rand, ref. [7].)

Fig. 3 (below). The relation between illumination and 'differentiation rate' for three sizes of detail and two degrees of contrast, using test object similar to that for Fig. 1 but with controlled exposure time. The conclusion drawn from Figs. 1 and 2 is confirmed, i.e. adjustment of illumination to yield equality of performance of the different visual tasks is impracticable. (Shaikevich, ref. [4].)





tween the contrast threshold data for a simple test-object of standard size as obtained under laboratory viewing conditions, and the different size and contrast of any actual practical task as ordinarily seen by dynamic vision. An essential preliminary to the use of this factor is the finding of some degree of contrast of the standard test-object which is equal in visibility to the contrast in the real task when this contrast is artificially changed to one that is only just perceptible. A form of visibility meter, already referred to as the Task Evaluator, is used for this equating operation, which is by no means easy to achieve accurately. The equating process obviously entails disguising the real task by changing its appearance until it is barely recognizable. Whether this procedure and the reliance placed upon it is justifiable on psychological grounds is questionable. But, having found in this way an 'equivalent contrast' value, which thereafter becomes the 'stand-in' for the real task, it can be used to enter a luminance specification curve, each point of which is higher up the contrast scale than the corresponding point on the threshold curve by the same factor, namely the 'field factor'. And the magnitude assigned to this factor has—to use the apt expression of Ward Harrison[14]—'tremendous leverage where the illumination values are high'.

In his latest paper[1] on this method for specifying illumination levels, Blackwell recognizes the need for a range of 'field factors' to describe all visual tasks, instead of only one such factor as in the currently recommended version of his system. He also recognizes the need for a range of levels of 'visual capacity', i.e. 'APS' or 'rates of discrimination', instead of only one. He states, moreover, that 'there is no adequate factual basis for assigning levels of visual capacity and field factors to actual practical tasks at this time'. However, he has assigned such levels on an 'intuitive' basis to fifty-six selected practical tasks and has shown how very different the prescribed value of luminance for any particular task may be according to the APS level and field factor value one intelligently guesses to be appropriate for that task. From his table of 'light factors' for various FF and APS values it is apparent that for a task rated by his VTE as having a log equivalent-contrast value of $-\cdot300$ the recommended luminance will differ by a factor of more than 2,000, according to whether FF5 together with 5APS or whether FF20 with 30APS is deemed appropriate. Blackwell concludes that 'it is going to be necessary to develop fairly precise procedures for selecting values of the visual capacity level and the field factor if the system is to have reasonable precision'. This seems at once to make any claim that the system in its present state, and especially in the form recommended for current use, is more 'scientific' and yields more valid values of illumination than other systems quite untenable. Moreover, it now appears that the VTE is not a substitute for task analysis, since such analysis has still to be done for the purpose of finding what values of FF and APS are appropriate.

There is, however, another serious source of error in Blackwell's system which has been pointed out by Ward Harrison and also by Hopkinson.[14] Blackwell's field factor is an omnibus one which is demanded by the system in order that working values of luminance for practical tasks may be derived from the relation between luminance and contrast sensitivity as determined under the 'unnatural' conditions of his laboratory experiments. The factor has several components, one of which is a factor of $2\cdot5$ which Blackwell says will always be necessary to allow for the criterion difference between laboratory and common-sense seeing; that is to say, to allow principally for the difference in contrast-sensitivity between trained laboratory observers operating in particularly favourable conditions and 'naive' observers doing ordinary practical tasks. This factor seems quite unjustifiable since people who do 'real' jobs regularly, e.g. inspectors, may be as contrast sensitive as the most practised laboratory observers. Other investigators[15] have found only negligible differences between the results of trained and 'ordinary' subjects. Even if this component of the FF is taken as 2, instead of $2\cdot5$, its elimination would reduce a luminance specification of 1,000 foot-lamberts to one of only 5 foot-lamberts. Other components of the omnibus FF are also open to doubt.

One further comment seems necessary. In using the visual task evaluator Blackwell states that 'it would be preferable to evaluate various tasks at luminance levels near the ones which will be eventually specified'. This appears only to mean that one should know the answer fairly well before asking the VTE to give it! More detailed examination of this new method would be out of place in this paper; enough has been said and quoted to make it evident that recommendations based on it can have no better standing than those based on the simpler British system; nor is there reason for supposing that they are likely to be better validated when tested in actual practice.

(4) Amenity Luminance

Before considering the prescription of levels of illumination for promoting efficient occupational seeing, it will be convenient to deal with the level desirable to provide adequate environmental or ambient luminance. This may be adequate for carrying on various kinds of work which are not visually very exacting but it will be considered here as mean-

ing the luminance desirable for affording amenity in the usual sense of this word, i.e. 'pleasantness of situation or of prospect'. This amenity—if not one of the 'rights of man'—is certainly something generally desired and always conducive to well-being. It is desirable in all interiors where substantial proportions of our hours of wakefulness have to be spent. But there is no one level of luminance which is appropriate for this purpose in every kind of regularly occupied interior. The 'average' environmental luminance which is gratifying depends on the character and usage of the interior. The luminance that will give the situation 'agreeableness to the eye' may well be lower in a lounge than in a workroom even if the workroom is used only for easy visual tasks, or if any difficult visual work is provided for by supplementary local lighting. However, the discussion here will be confined to the illumination for amenity luminance in places of work.

The 1945 I.E.S. Code recommended 6 lm/ft² as the minimum general illumination required for this purpose. The origin of this value was the 5th Report of the Departmental Committee on Factory Lighting[16] which, on the present author's advocacy in the interest of industrial morale, included the now historic recommendation that 'over the interior parts [of factories generally] in which persons are regularly employed the illumination shall not be less than 6-foot candles, without prejudice to any additional illumination required by the nature of the work'. To ensure the effectiveness of this level of illumination the Committee also recommended that all the principal surfaces which constitute the panorama in factory work spaces shall be maintained light in colour.

This recommendation of a minimum illumination high enough to afford 'reasonable amenity', and actually higher than the Departmental Committee had recommended for very fine work twenty years earlier, was revolutionary. The value itself was based on the findings from a lengthy industrial investigation completed a few years earlier by one of the author's former colleagues.[17] It was incorporated in the Factories (Standards of Lighting) Regulations, 1941,[18] which the Minister of Labour made in pursuance of section 5(2) of the Factories Act, 1937, but the auxiliary recommendation concerning surface colours could not be made the subject of a regulation. The Departmental Committee considered that the minimum level of 6 lm/ft² would not only provide amenity but would also be sufficient for 'ordinary work' to be done with ease.

In the 1955 revised edition of the I.E.S. Code 6 lm/ft² is still recommended as the amenity minimum (para. 13) but more generous general lighting is advised as a rule to 'enhance the satisfaction and feeling of well-being engendered by the bright appearance of the interior'. In fact, general lighting giving 'several times the recommended minimum' is suggested especially as this will also suffice for numerous tasks.

Up-to-date occupational lighting practice is usually consistent with this I.E.S. advice, that is to say, the general illumination provided exceeds the stated minimum amenity level. It is impossible to evaluate quantitatively the effect of this excess in terms of human well-being, and there is no new evidence, either subjective or objective, which points unequivocally to any specific value higher than 6 lm/ft² as being the least that should be recommended. It must be borne in mind that adaptation plays a very important part in determining whether or not an environment of given average luminance impresses us as being pleasantly bright. Actually, a non-uniform panorama of average luminance lower than would be given by a system of general lighting giving 6 lm/ft² on the usually specified horizontal plane of measurement can appear cheerfully bright if the illuminant is well chosen and there is a judicious use of sparkle.

However, from Ecclesiastes onwards savants have remarked on what is common experience, that the amenity of luminance may increase as the luminance is increased, up to levels well in excess of the one now under discussion. It was a student of human nature and not a lighting engineer who wrote, more than 100 years ago, 'our experience of a brilliantly lighted room exemplifies strikingly the pleasurable and exciting influence of a copious illumination'.[19]

Thus, although the current minimum of 6 lm/ft² can afford 'reasonable amenity', the recommendation of several times this value has behind it the weight of numberless experiences. Technical and economic difficulties, as well as inertia and indifference, have been responsible for tardiness in providing sufficient illumination for better amenity in many places. Nowadays quite liberal illumination is feasible and expected. Certainly in workrooms generally the ambient luminance should be made invigoratingly high: its amenity—its pleasantness—is due to its tonic effect in addition to, though partly because of, the enrichment and facility of general visual experience which it gives.

One way of indicating a better minimum amenity illumination than 6 lm/ft² would be to retain the familiar number 6 while changing the photometric unit to one of luminance. Thus, a recommendation of 6 foot-lamberts would lead to an illumination of at least 12 lm/ft² if say the reflection factor of the darkest sizeable element in the make-up of the panorama is used for computing the required illumination: this reflection factor will usually be less

than 0·5. There is, however, no magic in the number 6 and an amenity luminance of not less than 10 foot-lamberts in workrooms might well be recommended as good practice. But, if the resulting illumination value is made—so to speak—the 'ground floor' of the I.E.S. Code, at least for working spaces, the need for 'basement' values will remain. Expediency will sometimes demand them and they will not necessarily be physiologically inadequate.

(5) Working Illumination Levels

The author pointed out[20] prior to the issue of the post-war British I.E.S. Code that, although it is logical to vary illumination inversely as the 'lightness' of objects of critical vision, so as to bring the latter always to a common and satisfactory level of luminance for the size of object concerned, this can lead to very high illumination values when the size of detail is very small and the detail is itself a dark part of very dark material. But, besides this adjustment of illumination to compensate for differences among objects or materials in respect of their reflectivity, Beuttell[5] proposed a further adjustment to take account of the different degrees of contrast available for the discrimination of detail within objects, or for distinguishing an object from its immediate background. This adjustment was to be effected by applying a factor equal numerically to the inverse relative difference of the reflection factors of the contrasting objects of view.

These two factors—one for 'lightness' and one for 'contrast'—together amount to a single factor whose value is equal to the reciprocal of the difference between the two reflection factors involved in a contrast. The effect of applying this dual factor is to yield levels of illumination which give to all contrasts a common or standard luminance-difference whose actual value is a function of the size of detail involved. It has been shown[6] that this procedure does not fully compensate for differences of contrast although it works in the right direction. Its rigorous application would lead to still higher levels of illumination for fine detail of poor contrast and poor lightness than would the use of a correction factor for lightness alone. Beuttell's constant luminance-difference method is—as he was prepared to find—only partially successful as an antidote for degradation of contrast, but no more rational and simple method by which recommended illumination values may be selected according to visual-object contrasts has been proposed. The only way of making a very poor contrast as visible as a very good one is to view the latter in a visually handicapping illumination, that is, an illumination low enough to depress the

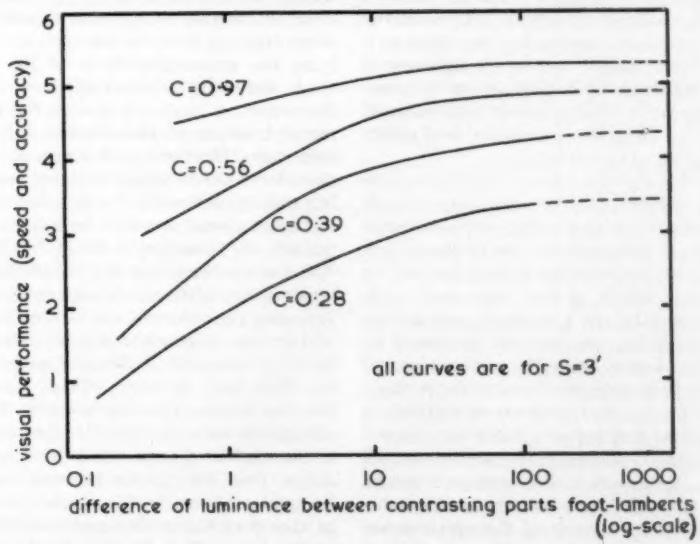


Fig. 4. The relation between visual performance and the difference of luminance between contrasting parts of a standard visual task object. Each curve relates to a different degree of contrast (i.e. to a different ratio of component luminances) but the size of the detail is the same for each contrast. It is evident that, if by different values of illumination for these different contrasts each of them is made to exhibit the same luminance-difference, there is no level of luminance-difference at which visual performance become equal for all contrasts. (Weston, ref. [6].)

ing the luminance desirable for affording amenity in the usual sense of this word, i.e. 'pleasantness of situation or of prospect'. This amenity—if not one of the 'rights of man'—is certainly something generally desired and always conducive to well-being. It is desirable in all interiors where substantial proportions of our hours of wakefulness have to be spent. But there is no one level of luminance which is appropriate for this purpose in every kind of regularly occupied interior. The 'average' environmental luminance which is gratifying depends on the character and usage of the interior. The luminance that will give the situation 'agreeableness to the eye' may well be lower in a lounge than in a workroom even if the workroom is used only for easy visual tasks, or if any difficult visual work is provided for by supplementary local lighting. However, the discussion here will be confined to the illumination for amenity luminance in places of work.

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In the 1955 revised edition of the I.E.S. Code 6 lm/ft² is still recommended as the amenity minimum (para. 13) but more generous general lighting is advised as a rule to 'enhance the satisfaction and feeling of well-being engendered by the bright appearance of the interior'. In fact, general lighting giving 'several times the recommended minimum' is suggested especially as this will also suffice for numerous tasks.

Up-to-date occupational lighting practice is usually consistent with this I.E.S. advice, that is to say, the general illumination provided exceeds the stated minimum amenity level. It is impossible to evaluate quantitatively the effect of this excess in terms of human well-being, and there is no new evidence, either subjective or objective, which points unequivocally to any specific value higher than 6 lm/ft² as being the least that should be recommended. It must be borne in mind that adaptation plays a very important part in determining whether or not an environment of given average luminance impresses us as being pleasantly bright. Actually, a non-uniform panorama of average luminance lower than would be given by a system of general lighting giving 6 lm/ft² on the usually specified horizontal plane of measurement can appear cheerfully bright if the illuminant is well chosen and there is a judicious use of sparkle.

However, from Ecclesiastes onwards savants have remarked on what is common experience, that the amenity of luminance may increase as the luminance is increased, up to levels well in excess of the one now under discussion. It was a student of human nature and not a lighting engineer who wrote, more than 100 years ago, 'our experience of a brilliantly lighted room exemplifies strikingly the pleasurable and exciting influence of a copious illumination'.[19]

Thus, although the current minimum of 6 lm/ft² can afford 'reasonable amenity', the recommendation of several times this value has behind it the weight of numberless experiences. Technical and economic difficulties, as well as inertia and indifference, have been responsible for tardiness in providing sufficient illumination for better amenity in many places. Nowadays quite liberal illumination is feasible and expected. Certainly in workrooms generally the ambient luminance should be made invigoratingly high: its amenity—its pleasantness—is due to its tonic effect in addition to, though partly because of, the enrichment and facility of general visual experience which it gives.

One way of indicating a better minimum amenity illumination than 6 lm/ft² would be to retain the familiar number 6 while changing the photometric unit to one of luminance. Thus, a recommendation of 6 foot-lamberts would lead to an illumination of at least 12 lm/ft² if say the reflection factor of the darkest sizeable element in the make-up of the panorama is used for computing the required illumination: this reflection factor will usually be less

than 0·5. There is, however, no magic in the number 6 and an amenity luminance of not less than 10 foot-lamberts in workrooms might well be recommended as good practice. But, if the resulting illumination value is made—so to speak—the 'ground floor' of the I.E.S. Code, at least for working spaces, the need for 'basement' values will remain. Expediency will sometimes demand them and they will not necessarily be physiologically inadequate.

(5) Working Illumination Levels

The author pointed out[20] prior to the issue of the post-war British I.E.S. Code that, although it is logical to vary illumination inversely as the 'lightness' of objects of critical vision, so as to bring the latter always to a common and satisfactory level of luminance for the size of object concerned, this can lead to very high illumination values when the size of detail is very small and the detail is itself a dark part of very dark material. But, besides this adjustment of illumination to compensate for differences among objects or materials in respect of their reflectivity, Beuttell[5] proposed a further adjustment to take account of the different degrees of contrast available for the discrimination of detail within objects, or for distinguishing an object from its immediate background. This adjustment was to be effected by applying a factor equal numerically to the inverse relative difference of the reflection factors of the contrasting objects of view.

These two factors—one for 'lightness' and one for 'contrast'—together amount to a single factor whose value is equal to the reciprocal of the difference between the two reflection factors involved in a contrast. The effect of applying this dual factor is to yield levels of illumination which give to all contrasts a common or standard luminance-difference whose actual value is a function of the size of detail involved. It has been shown[6] that this procedure does not fully compensate for differences of contrast although it works in the right direction. Its rigorous application would lead to still higher levels of illumination for fine detail of poor contrast and poor lightness than would the use of a correction factor for lightness alone. Beuttell's constant luminance-difference method is—as he was prepared to find—only partially successful as an antidote for degradation of contrast, but no more rational and simple method by which recommended illumination values may be selected according to visual-object contrasts has been proposed. The only way of making a very poor contrast as visible as a very good one is to view the latter in a visually handicapping illumination, that is, an illumination low enough to depress the

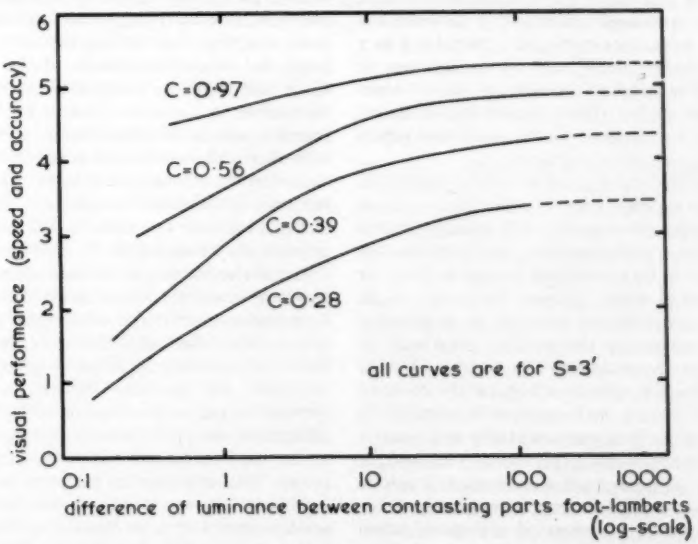

Fig. 4. The relation between visual performance and the difference of luminance between contrasting parts of a standard visual task object. Each curve relates to a different degree of contrast (i.e. to a different ratio of component luminances) but the size of the detail is the same for each contrast. It is evident that, if by different values of illumination for these different contrasts each of them is made to exhibit the same luminance-difference, there is no level of luminance-difference at which visual performance become equal for all contrasts. (Weston, ref. [6].)

contrast-sensitivity of the eye. Such a procedure would be irrational.

However, to prevent the maximum illumination in a scale of recommended values from being impracticably high, it was suggested in the author's 1943 paper that an arbitrary upper limit of 10 should be adopted for the dual lightness and contrast 'correcting' factor. This suggestion was followed in the 1945 and subsequent versions of the British I.E.S. Code and is exemplified in the highest of its three scales of illumination values. Thus, it will be understood that the current code system of specification can be regarded either as providing fairly thoroughgoing correction for the relative lightness of visual task objects and no correction at all for differences of contrast, or as providing a partial correction both for lightness and contrast. The new proposal about to be made involves acceptance of the first of these alternatives as one of the avowed aims of the system.

In applying the current code system to unscheduled occupational situations three features of the field of attention—the 'ergorama'—need to be isolated by analysis and evaluated. These are, (*a*) the critical detail to be seen, whose dimensions together with the distance from which it is viewed fixes its apparent size, (*b*) the criticial contrast, that is, the contrast between the criticial detail and contiguous elements of the object ('contained contrast') or between the object and its immediate surround if the object as a whole is the 'critical detail', and (*c*) the lightness of the object as indicated by its average or its dominant reflection factor. To ascertain the contrast, otherwise than by subjective estimation, two reflection factors require to be evaluated.

It is thought that this procedure is rarely practised and that some simplification is admissible without seriously lowering the precision with which desirable or optimum values of illumination can be assigned to particular tasks by any currently known methob, or the precision with which, in fact, they need to de assigned. The simplication consists in eliminating the need for measuring the contrast presented by task-objects, thus leaving only the apparent size of detail and the highest reflection factor in the contrast to be found. Inherent task contrast is certainly a factor which affects task performability but, since it is not compensable in this respect by any reasonable and systematic adjustment of illumination, it can be taken into account sufficiently well by suitably defining the performance criterion of the specification system. At present this criterion is not defined numerically. Recommended values are merely claimed to be 'of the right order for efficient seeing'. Often the criterion degree of efficiency has been quoted as 90 per cent but this is simply the level of relative visual performance suggested as reasonable in the author's 1943 paper on this subject.

It is now suggested that the criterion should still not be defined as a single level of relative *visual* performance but as a 'zonal level', and this level should have a band-width extending from about 90 to 100 per cent. Then, from the available experimental data, a level of luminance for each size can be found which is consistent with performance to the lower limit of the criterion when the task contrast is poor and with performance exceeding this lower limit when the contrast is good. Thus, the standard luminance is made dependent only on size of detail, and the actual illumination required to produce this standard luminance is dependent only on the lightness of the task-object or material. The lightness is proportional to the average reflection factor but, for the purpose of the method now proposed, only one reflection factor need be measured—the highest involved in the critical detail—since the necessary values of standard luminance can be specified on this basis. A lower limit of 0·1 is suggested for the reflection factor to be used in deriving illumination values from the standard luminance.

It is found from performance data published in 1935 and 1945[8] that simple empirical relationships between size and luminance can be formulated to satisfy the broad criterion proposed above. This criterion, despite its apparent latitude, is somewhat more exacting than the less explicit criterion underlying the recommendations of the current I.E.S. Code and so, if the proposals now made commend themselves, a moderate general increase in recommended values of illumination will be consistent with them. However, such a general increase is not considered to be warranted by any more recent data but only by adoption of a higher criterion.

The proposed standard luminance (SL) is given numerically by antilog $(2 \cdot 25 - 1 \cdot 5 \log S)$, or by $SL = 178 \cdot S$ where the unit is the foot-lambert and S is the apparent size of detail in minutes of arc. The performance data available refer only to sizes from 1 to 10 mins. and to values of contrast (relative reflection factor difference) down to 0·25. The size range is wide enough to cover easy to very difficult visual tasks. The contrast range, in association with the sizes, is also adequately wide: it extends to the contrast threshold at the smallest though not at the larger sizes of the range. Thus, the relation between size and standard luminance shown in Fig. 5 can be used for sizes smaller than 1 min. or larger than 10 mins. only by extrapolation. This is unimportant so far as larger sizes are concerned since the illuminations which would be found by extrapolation are lower than is required for amenity: in other words, the amenity illumination level is adequate for all tasks involving

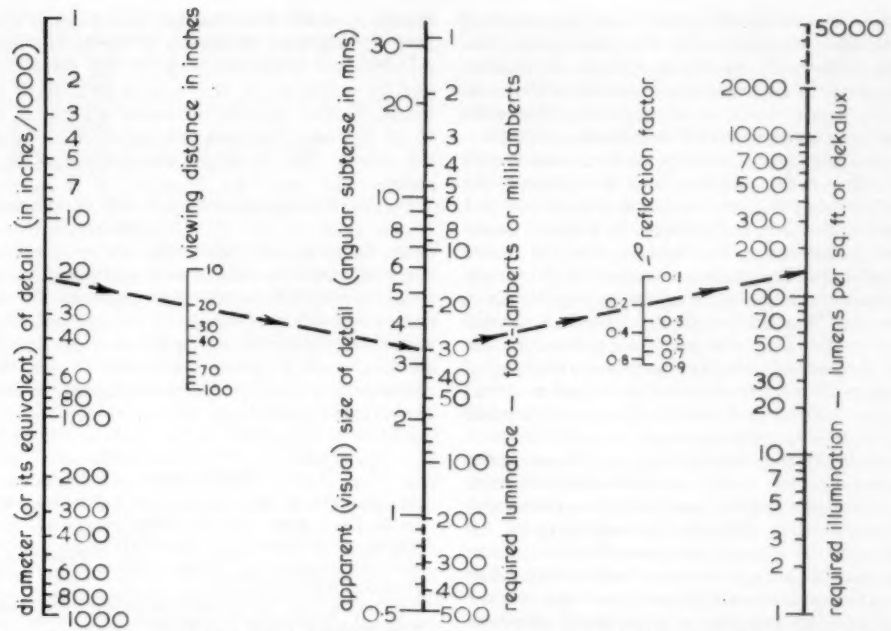
diameter (or its equivalent) of detail (in inches/1000)
viewing distance in inches
apparent (visual) size of detail (angular subtense in mins)
required luminance — foot-lamberts or millilamberts
ρ reflection factor
required illumination — lumens per sq. ft. or dekalux

Fig. 5. Nomogram based on the derived relation between size and luminance; the illumination required, according to the size and 'lightness' of the detail that needs to be seen, is found as exemplified in the diagram.

sizes larger than 10 mins., even if the lightness of the work-objects is low.

Beyond the other end of the size range extrapolation is also not very important. It is true that detail subtending a visual angle of only 0·5 min. can be seen by normal eyes with sufficient illumination, but such detail occurs in a very small proportion of practical tasks which are of the kind that could be better done with moderately high levels of illumination supplemented by optical aids than by 'superhigh' illumination and no other aid. However, assuming that the suggested size-luminance 'law' holds to the upper limit of average 'normal' visual acuity, it will be seen that it leads to a maximum illumination of 5,000 lm/ft² for the most difficult task. This is the 'ceiling' of the system. It would not be reasonable to put it any higher, for this may be taken as a natural limit and any task for which such a level is inadequate is not a naked eye task at all. In fact, it is not envisaged that illumination levels exceeding about 2,000 lm/ft² can be justified for any practical task and it is only for formal completeness that Fig. 5 is drawn up to the natural ceilings of illumination and acuity.

The lighting engineer is not primarily concerned with the recommended standard luminance but with the illumination he must provide to obtain it; this is given by antilog $(2{\cdot}25-\log \rho_1)-1{\cdot}5 \log S$ or by $E = \frac{178}{\rho \cdot S^{1{\cdot}5}}$ where the unit is the lumen per square foot and ρ_1 is the highest reflection factor involved in the critical detail. When S and ρ_1 are known the required illumination value can, if preferred, be read from the graph Fig. 5. It may be noted that with this method there is little point in dividing the gamut of visual tasks into a series of classes of difficulty. Each task rated on this basis is automatically put into place in an ordinal series by the value of illumination found for it and its 'illumination number' also ranks it for difficulty in the sense that concerns the lighting engineer. The higher the number the greater the difficulty but, of course, the ratio of two such numbers must certainly not be assumed to indicate how much more difficult one task is than another; a 100 lm/ft² task is not ten times as difficult as a 10 lm/ft² task.

A most important point has now to be made. The functional relationship which has been described between size, luminance and illumination is a practically convenient one which is derived from, but is

not the only relationship which could be supported by, the relevant experimental data. These data relate to the performance of self-paced tasks designed to typify some of the most important visual demands made by a great variety of practical tasks. They refer to the time taken under different levels of illumination to fixate each test-object, to scrutinize it until its detail was discriminated and then to shift the gaze to the next object. This is the ordinary method of seeing. The data also refer to the accuracy of the visual performance. The time required to give a manual indication that the prescribed detail was seen has been deducted from the task performance gross time. Thus it is evident that illumination levels found by the simplified method proposed in this paper properly relate only to the critical visual part of any practical task. If this critical visual part is of brief duration and of comparatively infrequent occurrence —and this is true of numerous practical tasks—it would not be unreasonable to discount the computed illumination if this is high; a somewhat lower value would have a negligibly small effect on the overall task performance and on the well-being of the worker. On the other hand, when there are features of the task which make it visually more difficult than the system under consideration allows for, e.g. if the task-objects are in motion or if the task is otherwise paced in respect of object exposure time, then the computed illumination may be increased to some extent. For the present—and perhaps always—any general rule governing the amount of such increase or decrease must be rather arbitrary. In the current I.E.S. Code an amount equal to one code step is advised and this means multiplying a computed illumination value by 1·414 for an increase and by 0·707 for a decrease. The Soviet code includes a similar rule and it is probably good enough for most cases.

The point being made is that the computed illumination is not necessarily what will be recommended finally in particular cases, but it is the basic value. The recommended values in the current British I.E.S. Code, as well as the new U.S.A. recommended values are all 'adjusted' for believed good reasons. It will be well to recognize that probably no specification system can be devised which will be omnicompetent. The proposals here made are no more than modifications of those put forward by the author in 1943. Now, as then, all that is claimed for the system to which they relate is that it is probably as exact as it needs to be for the uses to which such systems can be put. Mere multiplicity of 'factors' to allow for this and that will not necessarily make an illumination specification system more 'scientific'; it may well make it less so and may introduce a cumulative error that lowers the status of the end product to that of a guess. Whether one system is 'truer' than another in a practical sense must be judged by differences of results. If it makes no difference practically, e.g. to the performance and the well-being of users and to the costs of providers, whether the prescriptions of systems A, B or C are followed then any one system is as valid as the others. 'The proof of the pudding is in the eating.'

Finally, when code making, it may be salutary to bear in mind one of J. S. Mill's aphorisms: 'No one needs flatter himself that he can lay down propositions sufficiently specific to be available for practice, which he may afterwards apply mechanically without any exercise of thought. . . . Let us envelope our proposition with what exceptions and qualifications we may, fresh exceptions will turn up, and fresh qualifications be found necessary, the moment anyone attempts to act upon it.'

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Discussion

MR J. S. MCCULLOCH: Following the paper we heard this morning on 'Progress in the field of Electric Lamps' by Mr Jenkins, and in anticipation of the paper we are to hear on Wednesday, 'Plastics, Yesterday, Today and Tomorrow' by Dr Child, illuminating engineers could be forgiven for wondering what 'wind of change' was likely to blow in the field of specification and assessment of illumination levels. Those who have read Mr Weston's paper will perhaps think that the wind is tending to reach gale force in the USA, but here in this country the wind is more in the nature of a gentle zephyr.

In paragraph (3) of his paper, Mr Weston gives a brief resumè of two new recommendations, one from the USA and the other from the USSR, and he criticizes the new method from the USA. I find his criticisms sound and satisfying.

It seems to me wrong to claim that the USA system is 'scientific' because when it is found that for tasks measured by the Blackwell Task Evaluator, the levels of illumination range from 0·6 lm/ft² to more than 10,000 lm/ft², it is then necessary to use two factors, the range of field factors and the range of levels of visual capacity, which it is admitted have no factual basis but are based on intuition. Mr Weston gives us two examples of how slight variations in these two factors radically alter the ultimate result. In using an electronic computor the operator has to know how to feed the information into the computor before the computor can work out the answer, but Mr Weston has made it clear that to operate the Blackwell visual task evaluator, the operator has to know the approximate answer beforehand.

The Technical Committee of the Society is engaged on the preparation of a new IES Code, it being over five years since the last revision of the Code was made. The Technical Committee has delegated the task to a panel under the chairmanship of Dr W. E. Harper and a number of study groups are working on the various subjects dealt with in the Code, I being a member of the group concerned with recommended illumination levels.

It is the hope of the members of the Code Panel that today and tomorrow they will hear from members of the Society, their views on the various subjects forming the Code. It is hoped that there will be an active, provocative and critical discussion on Mr Weston's paper and, as a result, the members of the panel will be fortified in at least some of the decisions they have reached.

The panel has approved Mr Weston's proposals as a new basis for illumination recommendations, subject to weighting the experimental data to practical features associated with the tasks. Some examples of these practical features are: (1) the standard of visual performance expected in these days of the demand for maximum productivity, (2) the degree of amenity expected in the workshop in these days of higher standards of living and other factors associated with safety and economics.

It will not be claimed that the final recommendations are derived scientifically, but it will be claimed that they are based on experimental data tempered with commonsense, the commonsense being the vast experience accumulated by the scientific and practicing members of this Society.

It is the panel's view that insufficient grounds exist for abandoning the Beutell-Weston data which underlies the illumination recommendations of all earlier IES codes and consequently, it is proposed that the new code will use that data, but shaken up by the zephyr-like wind of change explained by Mr Weston in this paper.

The recommendations will be higher than in the 1955 Code. The higher standards of productivity, amenity and safety now expected, allied to the decreasing cost of light production because of more efficient lamps, justify the adoption of higher standards of visual performance and have led the Code Panel to increase the illumination levels for many tasks. They will be rationally recommended illumination levels.

MR J. M. WALDRAM: I feel that this subject is of extreme importance, and we are in Mr Weston's debt again for the clear thinking which he has brought to it.

We should all like to have more light if we can get it and if people are prepared to pay for it; but if reasons are to be adduced for having it which are alleged to be scientific, they must stand examination. I once quoted to the Americans the line: '. . . greatest treason to do the right thing for the wrong reason.'

It is very easy to simplify problems out of existence, only to find that one has solved the wrong problems; and I think that in the American work visual tasks have been simplified and factors multiplied together until figures have been arrived at which are obviously of the wrong order.

I would refer particularly to analysis of the task. If an observer is examining a screw (see illustra-

Fig. A. Object fixated and perceived in detail by foveal vision.

Fig. B. Object dropped on table: out of focus and away from fixation point. Found by parafoveal vision at low detail and subsequently fixated.

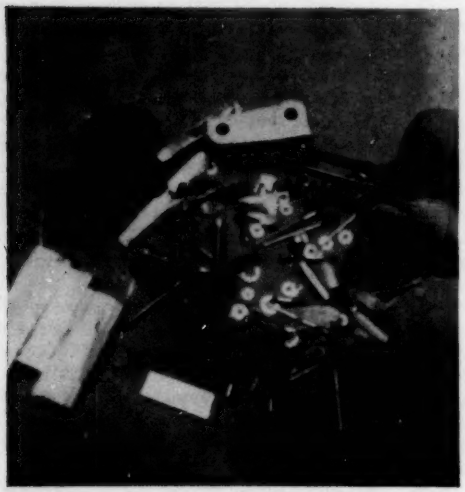


Fig. C. Object dropped on table among collection of similar objects. Parafoveal vision inadequate to dis.inguish it.

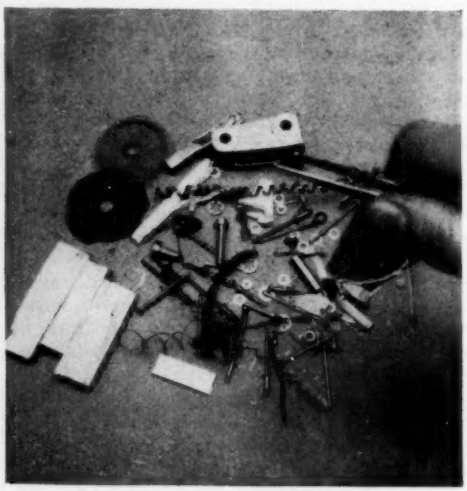


Fig. D. Situation as in Fig. C. Observer has to fixate objects in turn before he can identify the screw.

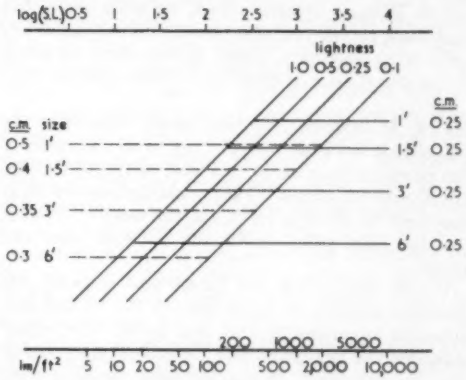
tion on this page) held in the tip of a pair of tweezers, he can locate it and fixate it immediately, because it is at the end of the tweezers, and can examine its fine detail. But if he drops the screw on to the table it will appear at first by parafoveal vision and out of focus. However, he only needs to locate it in order to pick it up, and that he can do very well by parafoveal vision, the main use of which is to locate objects which can be fixated if necessary. He does not need to see fine detail parafoveally. But if the screw falls among a number of other objects of comparable size and shape, parafoveal or peripheral

vision is unable to differentiate it. He must then fixate each object in turn, until he identifies the screw by its details, which may take him some time. More light will not help him to do it more quickly. In each of these cases, the luminance of the screw and of its background are identical: yet the visual tasks to be performed, and the time taken to do them are quite different, and cannot by any means be equated. In the light of such examples the procedure of equating of the task to a simplified test object by the visual task simulator and the conception of 'assimilations per second', based on the fact that one can assimilate one very simple bit of information in a given fraction of a second, seems quite absurd.

MR W. ROBINSON: I have always been very impressed, as I think all of us have, with Mr Weston's combination of science and sanity. May I say that Mr Weston is too good a scientist to blind us with science?

I think he has the right answer to this problem, that is the illumination for a specific task, but I do not think the illumination levels are necessarily bound up only with the work people are doing. Mr Weston has proposed that we should give a large proportion of our attention to amenity luminance, that is, the light people want because it is light—the psychological feature. I would like to see special attention paid to those features of modern life which might affect our attitude to illumination. For instance when we consider the windowless factory we have to remember that, whether we like them or not, there are going to be quite a number of these buildings and people are going to work in them without the benefit of daylight at all, so that the electric lighting should be equivalent to the missing daylight, about 50 lm/ft². There is, in fact, a limit to what we can do on the basis of task analysis alone. We have to think of what people want in their particular environment. Another point is the question of supplementary artificial lighting in buildings where there are windows but the light cannot get deep enough into the interior. The level needed to balance up during the day may be twice that required at night. It is easy for our Code to mislead people on these matters by suggesting that the only thing that matters is the task to be done. Our new Code has a most important job to do in drawing attention to these particular aspects of illumination in addition to basic task requirements.

MR R. A. MARSDEN: In the final section of his paper, the author presents a simplified procedure for specifying illumination or luminance levels, which he suggests will result in a bandwidth of relative visual performance (RVP) extending from 90 to 100 per cent. From the author's 1945 data[6] and Kruithof's interpolation of this data[11] it can be seen that the application of the formula SL=antilog (2·25−1·5 log S) provides this bandwidth over a limited range of contrasts: moreover it appears that this range varies with the size of the critical detail in the task. The accompanying figure is a simplified version of the author's Fig. 5, with his 'size lines'



shown dotted on the left-hand side: beside each size value is given the approximate minimum contrast for which a RVP of 90 per cent could be guaranteed. Would it not be better to abandon the tidy formula and utilize the standard luminance graphs with size lines at positions which ensure RVPs of 90 per cent or more for a range of contrasts which is independent of detail size? The size lines shown solid on the right-hand side of the figure are those ensuring RVP's of between 90 and 100 per cent for contrasts between 0·25 and 1·0 whatever the detail size. When lighting levels are reconsidered in the future, two criteria could then be considered—the minimum RVP, and the minimum contrast for which this performance applies.

MR R. L. C. TATE: Speaking as a practitioner, there are one or two things which I feel might be simplified. One is the question of environmental brightness. This is obviously not necessarily related to illumination levels which may be very high on the horizontal plane, but decidedly low on the vertical. If you legislate for six foot-lamberts, it is going to be difficult to measure. It is straightforward to take a light-meter and say the minimum is 6 lm/ft², but if you have to make brightness measurements the ordinary chap may have some trouble making his calculations. I think that it might be useful to develop a simple reflection-factor chart so that it would

be possible for the lighting engineer to arrive fairly easily at the brightness figures.

The other thing is that so much emphasis has been placed on foot-candles (I think that this term is better in this context) that people outside our field, for example, architects, have become foot-candle conscious. They will often ask you to give them the average illumination in a room when it doesn't really matter a hoot how much it is. If we are to increase lighting values, we must make sure that these people can understand that this is not the only thing necessary, other factors must be taken into account, such as modelling, diffusion and colour.

DR W. E. HARPER: Mr McCulloch referred to the fact that it has been my privilege to be chairman of the panel responsible for revision of the IES Code, and it may be helpful if I can indicate how the ideas described by Mr Weston fit into the work of revision that has been going on for the last two years and more.

In the first place the panel has adopted Mr Weston's suggestions as the basis of the revised illumination recommendations, and as Mr McCulloch indicated the new proposals are evolutionary rather than revolutionary. In making them we have tried to bear in mind to whom the Code is addressed, that illumination is only one aspect of the Code, that the recommendations must be consistent and be related to the standard of living. The plea that we should recommend much higher values would be more persuasive if evidence was available that such increases result in increased production, less scrap and less absenteeism, but it is just such information which I find to be almost wholly lacking. My own feeling is that until the industry can produce this evidence it will be very difficult indeed to convince users of the value of these very high levels of illumination.

Now what of the future? It is my personal view that this may well be the last edition of a code of this type and that in five or ten years time we shall have a code with a different and much broader approach to lighting practice. It may well be based on subjective appraisal and there is no doubt that few countries are as well equipped as we are to undertake this work. It would cost money but I am sure that it would be money well spent.

MR J. F. PICKUP: If Fig. 5 is to be printed in the new IES Code then the lines at 45 degrees across the diagram, and the figures for reflection factor (lightness) should be printed in colour. It is not clear that each of the figures for lightness has a corresponding line. Although the term 'lightness' is used in the present Code surely 'reflection factor' is better. A worked example on its use, and on the formula on which it is based would also help to make it more easy to understand.

A slide was shown of the relation between subjective contrast and object size; could this be published in the final version of the paper?

With reference to the formula by which the required illumination can be calculated without reference to Fig. 5, it seems to me that if the highest reflection factor of the task is taken and used in the formula, then there is a possibility of the Code being misapplied and too low an illumination specified.

A small criticism of the present Code is that it is difficult to read. The sentences are somewhat long; there are no pictures to enliven its pages, and few diagrams to clarify its rules and recommendations. There is perhaps too much emphasis on architecture. I think we can learn a lesson from the Americans here. Their Code is a bad example of good salesmanship and ours a good example of bad salesmanship. The American IES publications are set out with plenty of clear black and white line diagrams and they are not afraid to use photographs. I think some of the impact of the present British Code has been lost simply because it is difficult to read and has therefore been left unread.

MR K. R. ACKERMAN: The paper refers to weighting factors to be applied to the recommended illumination levels to allow for variations in contrast for a specified task. I think recommended illumination levels would also have to be adjusted to allow for other variables. One such variable is the age of the people doing the task. Would the author consider recommending a multiplying factor of $\sqrt{2}$ for illumination levels for workers over 50 years of age and a further $\sqrt{2}$ for workers over 60.

Another consideration is a weighting factor to be applied to fluorescent lighting as in the Russian Code. In the paper this is dismissed as being due to the limitations of wiring, but I do not think this subject can be so readily dismissed.

There appear to be some phenomena in fluorescent lighting which scientific investigation has not yet satisfactorily sorted out. The interaction of flicker and ocular motor frequencies for example. I believe there is published work which indicates that performance under fluorescent lighting may be inferior. This is a subject certainly worthy of further research and a consideration which might well be borne in mind by those responsible for the preparation of future Codes.

MR J. G. HOLMES (communicated): The master diagram given as Fig. 5 of the paper can be reduced to a single equation relating several variables namely, illumination level, size of detail and luminance factor

involved in the critical detail. The equation is given in logarithmic form in the latter part of the paper, but I find it easier to understand it written in algebraic form as follows:

$$E = \frac{180}{\rho_1 . S^{1.5}} \text{ or } E.\rho_1.S^{1.5} = 180$$

The product $E\rho_1$ is of course the luminance corresponding to the highest reflection factor involved in the critical detail, expressed in foot lamberts, and the basic standard luminance equation is therefore as follows:

$$L = 180.S^{-1.5} \text{ or } L.S^{1.5} = 180$$

The limits within which these formulae may be applied are as follows:

S 1·0 minute of arc to 10 minutes of arc
ρ_1 minimum value 0·1
E minimum value for amenity 10 lm/sq.ft. or perhaps 15 lm/sq.ft. maximum value 2,000 lm/sq.ft.

It is interesting to see that the first formula given above is very similar to the formula suggested by Mr Weston in his 1943 paper 'Proposals for a New Lighting Code' on which the current IES Code has been based. This lends support to his argument that the basic relations between size, reflection factor and illumination level have been known for many years, and that the present recommendations are in accordance with a well-established formula which has been proved in the past and which is now set at a level to suit the present standard of living and the present economics of lighting.

THE AUTHOR (in reply): Mr McCulloch's interesting opening comments fortunately do not set me any questions to answer. In raising his point concerning task analysis, Mr Waldram has—if I may modify a metaphor—'hit the screw on the head'. I hope the photographs used to make this point can be included in the published discussion. It is interesting to note Mr Robinson's remark that in windowless factories the equivalent of the missing daylight would be artificial lighting to a level of about 50 lm/ft². I think his figure is not very wide of the mark, that is to say, in factories that have good natural lighting the average daylight illumination during average days is unlikely to be much greater than 50 lm/ft². This is very different from the much higher levels for general artificial lighting advocated by a few exotic enthusiasts. There is a lack of convincing evidence that such high levels give to *adapted* persons a significantly more satisfying impression of environmental brightness than does the level Mr Robinson mentions. The higher values that are commendable for unusually difficult tasks relate to the actual task objects and must often be got by local lighting if the work is to be brighter than its surrounds.

I am grateful for Mr Marsden's constructive criticism. The modification he suggests is clearly a possible alternative that accords with the data and has this to commend it. With some compromise, however, it need not involve abandoning the 'tidy' formula but only changing its constant from 2·25 to 2·55. Inspection of Mr Marsden's figure shows that the values of luminance required to satisfy the criterion he proposes are in very nearly the same ratio as those given by my formula for sizes 1 to 3 mins., although they are twice as high. It is only at 6 mins. that the modified formula fails to agree with Mr Marsden's figure, since, for this size, it gives a value which is higher by about 14 per cent than the value needed to satisfy Mr Marsden's criterion. This may be regarded as an error in the right direction, i.e., it should put the limiting contrast for this size somewhat lower than 0·25. The disadvantage of the graphical method suggested by Mr Marsden is that it involves an irregular size scale which would make interpolation difficult. There is, I think, much to be said in favour of a 'tidy' formula provided it can be memorized readily and be worked easily and, of course, provided there is reasonable justification for its terms. It can also be represented graphically for those who prefer to read a graph rather than use a formula. I have substituted a nomogram for the Fig. 5 shown in the preprint of my paper so as to graph the formula in the most convenient way. While Mr Marsden's criterion would lead to higher levels of illumination than mine, so that the gap between British and American recommended levels would be narrowed, I feel that field validation becomes increasingly important as levels are advanced, and I do not think that present knowledge of this kind is sufficient to warrant higher levels than can be derived on the basis I have proposed. Dr Harper evidently shares this view. It is very likely that in future codes the utilitarian aspect of illumination will be given less emphasis than now, because the trend of practice will have led to prevailing levels which are sufficient for perhaps more than 90 per cent of practical visual tasks. It will then be important chiefly to ensure that lighting techniques are employed which enhance the amenity of lighting in other aspects than mere adequacy of illumination.

Mr Pickup will find that most of his points are met in the present version of the paper, particularly by the re-drawing of Fig. 5 in the more usual form of a nomogram. The diagram he mentions, which gives some indication of the relation between objective (luminance) contrast and apparent contrast at different sizes of object, is to be found in reference[8].

The formula in the paper gives values of illumination which bring all objects of a given size to a standard luminance in respect of that part of them which has the highest luminance factor, because the standard luminance has been chosen to be satisfactory on this basis.

Mr Ackerman's suggestion that the illumination levels found by the method described should be weighted for persons over middle-age is, I think, being adopted by the Code Panel. The data relied on in my paper refer to an average age of about 37 years, so the values of illumination given by the formula will be reasonably good for people up to the age of 50. For older workers they might be multiplied by a factor of 1·5 or 2 but, optical aids are more effective than going higher than this. So far as I know, the only controlled experiments that have been made to compare visual performance under fluorescent and incandescent lighting giving the same illumination are those made some years ago by Dr W. F. Floyd for the Post Office. They revealed no significant difference. The fact that the Russian code advises fluorescent lighting for preference where visibility needs to be particularly good, does not suggest to me that higher levels are specified because fluorescent lighting is considered to be less effective; the inference seems to be that since 'fine ' work needs high illumination the illuminant of choice should be the one that yields the higher level for a given load. However, I do not want to suggest that there may be nothing left to learn about the effects of fluorescent lighting.

Following Mr J. G. Holmes' suggestion that the formulae given for standard luminance and for working values of illumination should be expressed in algebraic form, I have added these in the paper as now printed. While the limits of size within which Mr Holmes says the formulae can be applied cover the range actually investigated, these formulae are biassed towards large sizes, i.e., they yield values for these which are higher than the experimental data require. Therefore, if the formulae are applied to sizes larger than 10 mins. and up to the limit shown in Fig. 5 they will give values that will almost certainly satisfy the performance criterion, although they may be below the amenity level.

UDC 621.32

Progress in Electric Lamps

By H. G. JENKINS, M.Sc., F.Inst. P. (*Member*)

Summary

During the past twenty-five years there has been spectacular progress in the development of electric lamps. While this applies mainly to discharge sources, much work has gone into incandescent lamps, which, despite their relatively low luminous efficiency, have not diminished in importance. An entirely new method of converting electrical energy into light by electroluminescence has been evolved, which, however, has not fulfilled its early promise. On the other hand, at a time when progress in conventional discharge sources might reasonably be expected to have levelled off, new ideas have evolved and substantial improvements have been made. The paper discusses the more important developments and trends in the field of electric lamps.

(1) Tungsten Lamps

Despite the widespread use of the newer and much more efficient discharge lamps, the tungsten filament lamp is still the most important light source in common use. Among the many factors which make this so, perhaps simplicity, cheapness and excellent colour rendering characteristics stand out. For these reasons, and because of its small size which enables a wide range of lighting effects to be obtained easily by the ordinary user, the filament lamp is still very largely used for lighting the home.

The history and development of the tungsten filament lamp have recently been the subject of a comprehensive review,[1] and it is not intended in the present paper to do more than mention some recent trends and developments.

(1.1) Bulb sizes

During the past few years a great deal of attention has been given to reducing the bulb sizes of the General Lighting Service (G.L.S.) range of tungsten lamps to reduce manufacturing costs. The bulb size of a tungsten lamp is mainly governed by its wattage rating but in addition to cap and bulb temperatures, lumen maintenance is a limiting factor. The maintenance worsens if the bulb size for a given wattage is reduced beyond a certain limit because of the greater concentration of evaporated tungsten. Up to a point this is offset by the greater gas pressure developed inside the smaller, and therefore hotter, bulb, which reduces the evaporation rate. Variations in filament location within the bulb can also modify the lumen maintenance, as is demonstrated in the American G.L.S. axial filament lamp where most of the evaporated tungsten is confined to a small region of deposition on the crown or in the bulb neck.

The bulb and cap temperatures obviously increase as bulb size is reduced, although the temperature can be controlled to a certain extent by lamp design modification. Undue increase in bulb temperature may affect lamp performance because of release of gas from the hot glass and too high a cap temperature may cause the cap to loosen. Nevertheless, the great advances that have been made in lamp-making technology, and particularly in capping cements, have made possible substantial reductions in bulb sizes of G.L.S. and decorative tungsten lamps, without detriment to lamp performance; technically speaking, the ultimate in this direction has not yet been reached. The practical limitations on reduced bulb size are no longer determined by the quality and performance of the lamp, but rather by the economics of the lighting fittings, lampholders and cable; further reductions may have to await the agreement of lamp, fittings and cable interests. Table 1 gives the present bulb dimensions of G.L.S. lamps in the range 40 to 150 watts. The earlier values are given for comparison together with possible future dimensions.

A study has been made of the possibility of a heat source which will operate at a cap temperature representing the maximum likely to be encountered from the smaller size G.L.S. lamps and which can, therefore, be used as a standard reference by the fittings designers and manufacturers. This is a most important development and offers a degree of much-needed stability to both the lamp and fittings interests. The result can only be a closer understanding of mutual problems in the future and a better combined performance of lamp and fitting.

(1.2) Bulb shape

Apart from reductions in bulb size there have been departures from the conventional shapes hitherto used for general purpose lamps. These changes in shape are largely determined by aesthetic appeal and

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the satisfaction of public demand for something new and inherently attractive. Thus mushroom, and cylindrical shaped bulbs (Fig. 1) have been marketed in recent years for general lighting. In addition, spherical and candle-shaped bulbs, used for more decorative lighting, are now commonplace. It sometimes happens that a device introduced for its novelty value proves to have unexpected advantages. For example, there is some evidence to suggest that the cylindrical bulb may be better than the conventional shapes for use under dusty conditions.

An attractive new lamp has recently appeared in the United States in which a highly decorative bulb is used. This is known as the 'Celeste' lamp and it is, in effect, its own lighting fitting; its introduction provokes some interesting thoughts on future possibilities.

(1.3) Projector lamps

Recent developments in projector lamps are important because of a new approach to the relation between the light source and its optics. Whereas previously the lamp and the optical system in which it is used have been separate components, new lamps are now being introduced which have their own parabolic or elliptical section reflectors. Associated with these developments there is also an important trend towards low-voltage (8 to 20v) lamps which make possible a thick and robust filament with associated advantages of compactness and higher luminance.

The earliest lamp of this type with precisely controlled optics was the well-known sealed-beam lamp with pressed parabolic reflector and front glass. First introduced in America for vehicle headlamps, it is now being widely used, as is the earlier mould-blown reflector lamp, for spotlighting, external floodlighting, airport lighting, and even for pleasant unobtrusive general lighting in new office blocks. Production facilities for the sealed-beam lamp, which require considerable capital outlay, are now available in this country.

Recent introductions of projector lamps with integral reflectors are the 8v 50-watt elliptical reflector lamp for 8 mm. ciné projection, developed in Holland, which gives a greater screen luminance than the hv 500-watt lamp with conventional optics; the American high wattage biplane projector lamp with small internal molybdenum mirror which gives 20 per cent greater screen luminance than normal; and more recently, also from the U.S.A., a lamp with attached external reflector which is accurately adjusted before leaving the factory. Some of these are shown in Fig. 2.

(1.4) The Tungsten-Iodine cycle

Perhaps the most important development of recent

Table 1

Dimensional changes in G.L.S. tungsten lamps in the 'domestic' range

Wattage	Bulb diameter and overall length (*millimetres*)		
	Immediate post-war	Present	Possible future dimensions (Approximate only)
40	60 × 110	60 × 105	60 × 102
60	65 × 117·5	60 × 105	60 × 102
100	75 × 137·5	68 × 125	60 × 102
150	80 × 160	80 × 160	70–75 × 120

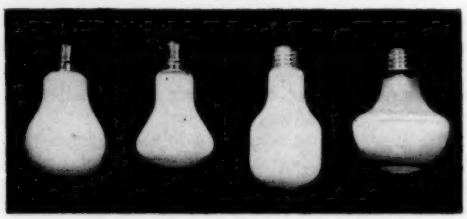


Fig. 1. *Bulb shapes of general purpose incandescent lamps.*

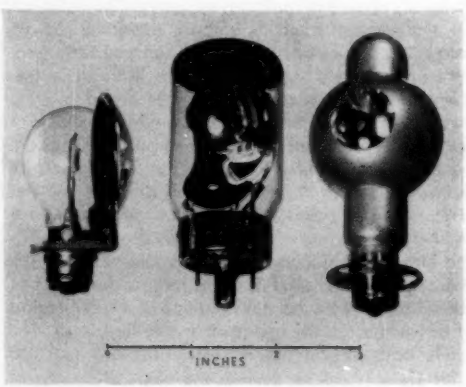


Fig. 2. *Projector lamp design.*

years in filament lamps is the deliberate use of chemical mechanisms in the lamp to improve lamp performance. Solely physical processes, filament temperature and evaporation characteristics of tungsten in an inert gas atmosphere, have heretofore controlled the light output and have given tungsten lamps their well defined efficiency-life relationships.

In 1915 Langmuir described the influence of chlorine on incandescent tungsten[2] and noted that if incandescent and 'cold' tungsten wires were placed side by side in a chlorine atmosphere the hot wire would increase in diameter at the expense of the cold wire which would eventually disappear. During the following thirty years there appeared further references in the literature to the addition of halogens or halogen compounds to tungsten lamps. In 1953 a study of the influence of iodine on the arcing characteristics of G.L.S. lamps was started at Wembley, where it was noted that when a fair quantity of iodine was added to the normal gas filling in a lamp a very pleasantly tinted pink lamp was produced whose colour remained stable and whose life was greater than expected.[3] This was a most interesting result since it showed, contrary to expectations, that a practical incandescent tungsten filament could be operated satisfactorily in an iodine atmosphere provided that the usual nickel support leads are replaced by molybdenum. Other halogens were unsatisfactory because of their considerable reactivity, even with molybdenum.

At about this time the G.E. of America were developing the quartz tubular infra-red lamp with a tungsten filament which, because of rapid and serious bulb blackening, looked singularly unpromising as a light source. They began to explore the potentialities of iodine and discovered that with iodine present the quartz tube remained quite clean even when the nearby tungsten filament was at a temperature of 3000°K.[4] This remarkable effect has since received much study, both in this country and abroad. It is now known that for the effect to occur three conditions must be satisfied, namely, the wall temperature of the enclosure must be over 250°C, its size and shape must be such that the gaseous convection currents within the lamp are negligible, and the chemically reactive components within the enclosure must be confined to tungsten and iodine. These reactive constituents, in the possible presence of an inert gas, form a closed chemical system in which the tungsten and iodine components are continually combining and dissociating. The iodine prevents tungsten condencing and remaining on the envelope by forming a tungsten-iodine compound which remains in the vapour state and diffuses through the lamp volume. This compound does not dissociate until it reaches a temperature of over 1,600°C in the neighbourhood of the filament. When dissociation occurs it has, therefore, the effect of increasing the pressure of tungsten vapour near the filament so reducing the evaporation rate. Thus, in addition to making possible a nearly perfect lumen maintenance, the tungsten-iodine mechanism improves the lamp life by reducing evaporation of tungsten. The temperature and convection condition mentioned above for the operation of the iodine cycle necessitate small envelope size and point to quartz as the most suitable material.

(1.5) Practical Tungsten-Iodine lamps

There are likely to be many repercussions from this development in our thinking on lamps and lighting. It offers us, for example, extremely small, high brightness lamps of outstanding performance for 8 mm. or 16 mm. ciné projection. This type of lamp used with a small, short focus elliptical reflector makes possible a highly efficient arrangement in which the lamp and its optical system are separate with all the advantages this entails of economical lamp replacement. Fig. 3 shows an experimental lamp of 12v 100-watt rating developed at Wembley, in comparison with the much larger conventional glass lamp of the same wattage. Another possibility is in a similar lamp used with a small short focus reflector for spotlighting or floodlighting.

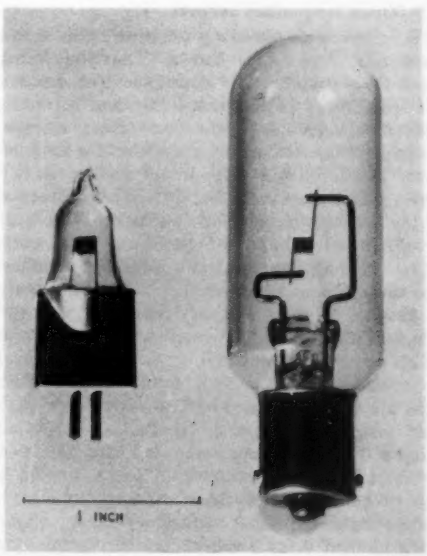


Fig. 3. Experimental 12v 100-watt quartz-iodine projector lamp compared with conventional lamp.

Quartz tubular iodine lamps of higher wattage can be used for many applications of sports field lighting and floodlighting where the new source gives, in addition to a better performance, marked advantages in the size and cost of the fitting. Yet another way in which this development may affect our thoughts is in the field of tungsten ballasted high pressure mercury lamps (see Sec. 3.2).

(1.6) Lamp manufacture and performance

Advances in the technology of tungsten lamps continue. Speeds of G.L.S. lamp manufacture are increasing and this necessitates faster, more comprehensive, and more automatic methods of testing and checking at all stages in production. Automatic testing and rejection mechanisms for incorrect rating, open circuit, short circuit and low insulation faults are being carried out on the final product and further automatic tests are under development.

Although there has been continuous improvement in almost every aspect of lamp quality, much still remains to be done to improve the uniformity of lamp performance. The magnitude of the problem is apparent when it is realized that a change of only 1 per cent in the diameter of wire in the length of a single filament, can reduce lamp life by over 25 per cent compared to that using a uniform wire.

(1.7) Other temperature emitters

Tungsten, with a melting point of 3,653°K, is the most refractory metal known. This characteristic more than anything else determines the efficiency-life relationship of tungsten lamps and leaves little room for spectacular improvement. The properties of tungsten compel its use in the form of a long, relatively fragile, coiled wire, which further limits its performance as an incandescent body. The discovery of the tungsten-iodine cycle opens up considerable possibilities for improved performance in certain types of lamps, but to achieve much higher efficiencies from a temperatire emitter it will be necessary to discover a more refractory conductor than tungsten and preferably one which emits selectively and which can be used in the form of a thick rod.

Certain metallic carbides, notably tantalum carbide, are conducting and have melting points higher than tungsten.[5] A special type of projector lamp using a disc of tantalum carbide, heated to incandescence by eddy current heating from a radio frequency generator, has been demonstrated in the United States.[6] Another method of heating which is being studied is by electron bombardment, which may have application in heating highly selective emitters such as thoria and other semi-conductors. While all this work is of great interest there is nothing to suggest it is likely to lead to an important substitute for tungsten in the near future.

(2) Fluorescent Lamps

It is now just over twenty years since the fluorescent lamp in the form in which we know it was marketed in the U.S.A. It is just as well to remind ourselves that much of the basic work leading up to this event was done in Europe, and indeed this country can claim a major share in the credit for the development of this remarkable light source.

(2.1) The 5 ft 80-watt fluorescent tube

The first British fluorescent lamp to operate directly from a mains voltage supply was marketed in 1940 although experimental lamps of various sizes were already well advanced in the laboratories of some of the larger British lamp companies as early as 1937. At that time high voltage fluorescent lamps were already well established for lighting purposes in this country. (Perhaps it is even worth recording that the lounge of my home in Pinner was lit with cold cathode fluorescent and neon tubes as early as 1935. The colour rendering from the combination compared favourably with anything available today. I have no certain means of knowing if this was the first domestic fluorescent lighting installation in the world, but I strongly suspect that it was.)

The first British mains voltage lamp was the well-known 5 ft 80-watt lamp which was hurriedly introduced to meet the needs of wartime Britain; because of the excellence of the design it became, and still remains, the most important lamp in this country. In 1942 the efficiency was 35 lm/w for the 'Daylight' colour and a life of 2,000 hours. The efficiency is now greater than 60 lm/w, although it is only fair to say that about 25 per cent of this increase in efficiency can be accounted for by the change in the spectral distribution of the light which occurred when halophosphates were introduced in 1945. The discovery of this family of phosphors at Wembley in 1942 is probably the greatest single contribution to fluorescent lamp progress since its inception. The life of the lamp is today certainly closer to 8,000 than it it is to 5,000 hours. Failures before 4,000 hours are exceptional. (The large manufacturers have such faith in their product that they guarantee to replace, free of charge, any fluorescent lamp which fails before 3,000 hours or a year's burning.)

(2.2) Performance

In 1942 it was shown from theoretical considerations that the maximum efficiency to be expected from a low pressure fluorescent lamp was 60 lm/w for a colour close to that of natural daylight.[7] There

is still some way to go to achieve this performance but the gap is being filled more rapidly than might have been expected.

The improvement in the average efficiency throughout the life of the lamp, now usually taken as the efficiency after 2,000 hours burning, has been even more marked than the gain in initial efficiency. This is the figure that really matters to the user and in an ideal lamp it would be no lower than the initial value. It is a pity that the practice throughout the world is to stress initial values rather than average. Most people who think about this matter at all will agree that of two lamps having the same life and average efficiency, but different initial efficiencies, the one with the lower initial value is the better; and this is true for all lamps, not only for fluorescent tubes.

How have these improvements in performance been brought about? The life is mainly a function of the filamentary electrodes, each of which carries about 15 mgms. of electron emissive material in its coils. This comprises a mixture of alkaline earth carbonates which are subsequently decomposed to the oxides during the processing of the lamp. It is of great importance that the coating of oxides on the filament should emit electrons freely and that it should be firmly retained in the coils of the filament during operation. Attention to both these matters have, more than anything else, contributed to the excellent life performance of the lamp. The emissive material is gradually removed from the cathode while the lamp is burning and when no more remains the discharge will not start. There are other causes of failure, but this is the usual one.

The gain in luminous performance has arisen mainly from a steady improvement in the quality and particle size distribution of the fluorescent powder used for coating the inside of the tube. This, in itself, would have had little effect without corresponding improvements in the lamp manufacturing processes and equipment.

(2.3) The fluorescent coating

The phosphor as it comes from the furnace is a lightly sintered powder which has to be milled and suspended in a binder to enable a thin coating to be applied to the tube. The particle size distribution of a typical phosphor is shown in Fig. 4 (curve A) from which it will be seen that the range covered is from about 1 to 30 microns. It will be apparent that the coating must effectively prevent any U.V. radiation from the arc reaching the glass wall of the tube, where it would be absorbed and wasted. The optimum coating density is achieved at about 7·5 grms. of powder per 5 ft 80-watt tube with the distribution shown. For economic reasons it has been usual to

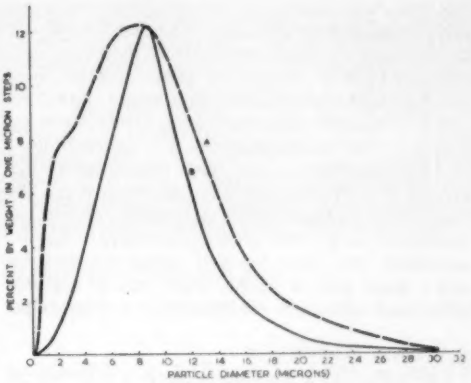


Fig. 4 (*above*). *Particle size distributions of phosphors.*

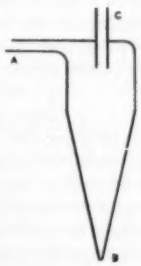


Fig. 5 (*left*). *Hydrocyclone.*

work slightly below the optimum at about 5·5 grms. per tube. It has long been known that the very fine particles in the phosphor below 3μ have a low intrinsic efficiency. Moreover, because they tend to form a U.V. absorbing coating over the larger crystals they have a disproportionate effect in reducing the efficiency of the lamp. The distribution curve B, shown by the full line in Fig. 4, is that of the same phosphor classified by removing the ultra fine particles and some of the coarse. One important method of doing this is to pass an aqueous suspension of the milled powder through a hydrocyclone shown diagrammatically in Fig. 5. The suspension enters at A, tangential to the inner surface, at a high velocity and flows down the cyclone in a spiral depositing the large particles on the walls from which they pass out through the orifice B. The finer particles are carried up the inner tube and out through C. A number of cyclones can be used in series to improve the separation. In the full process the coarse fraction is re-milled and re-classified, thus effectively cutting from both ends of the distribution. This technique is capable of handling many kilos of phosphor per hour with relatively simple equipment.

The use of classified phosphors has given an overall improvement in efficiency of about 10 per cent.

Unfortunately, because of the losses in the classification process, and the increased coating density due to the higher average particle size, this gain has only been achieved at the cost of about a 40 per cent increase in phosphor usage. In a recent paper[8] referring to particle size control of phosphors there is a mention, without amplification, of a figure of 80 to 85 lm/w for 40-watt white tubes. Zero hour figures of this order have been achieved in most of the laboratories of the large lamp manufacturers in experimental lamps with special gas fillings. They are associated with poor life and lumen maintenance and a great deal of further work will be required before such efficiencies are obtained in normal lamps.

(2.4) Colour characteristics

The colour of a fluorescent lamp is specified by its C.I.E. chromaticity co-ordinates which define the colour appearance of the lamp; the luminance in eight spectral bands, into which the visible spectrum is arbitrarily divided, give a measure of the colour-rendering properties of the lamp.

Fluorescent lamp colours tend to fall into regions with chromaticity values not far from those of a full radiator at 6,500°K, 4,500°K, 3,500°K and 2,850°K as shown in Fig. 6. It is for this reason that the colours are sometimes decribed as 6,500 White, 4,500 White and so on. It is convenient to do this but the measured chromaticity values must be used for accurate specification purposes.

It is possible to have two fluorescent lamps of closely similar colour appearance but having markedly different colour rendering characteristics. As might be expected, the lamp with the better colour rendering usually has the lower efficiency. Associated with each of the main white colour regions there is a high efficiency lamp and a so-called de luxe lamp, giving an improved colour rendering but a lower efficiency. By ringing the changes in the composition of the fluorescent coating it is possible to produce a wide range of white colours. This situation, as well as being a source of embarrassment to the lamp makers, can lead to difficulties in standardization. Recently yet another colour was added to the range marketed in this country. The colour appearance of this is similar to 'Natural' and the emphasis is on good rendering of colours, particularly in the red region. The average-through-life efficiency in the 5 ft 80-watt rating is rather less than 30 lm/w. It is, at least, questionable if there is justification for two de luxe colours in this region, and it is to be hoped that one will in due course become redundant.

Although the major part of the light from a fluorescent tube comes from the fluorescent coating, something like 10 per cent comes from the mercury vapour discharge. In the warm-colour lamps there is little blue radiation from the coating and the blue and purple lines in the mercury spectrum supply most of the blue light. These lines cause distortion of the rendering of blue colours which is a characteristic of warm fluorescent light to which some people are very sensitive. The effect can be largely overcome by selective filtering of the mercury radiation, either in the lamp itself or in the fitting; double-coated lamps of excellent colour have been introduced in which the coating in contact with the tube wall acts as a filter for the blue mercury lines. It is possible by this technique to reproduce fairly accurately the colour appearance and the colour rendering characteristics of both low and high temperature tungsten filament lamps.

(2.5) Highly loaded lamps

Until a few years ago when lamps of similar loading were announced in the U.S.A., the 5 ft 80-

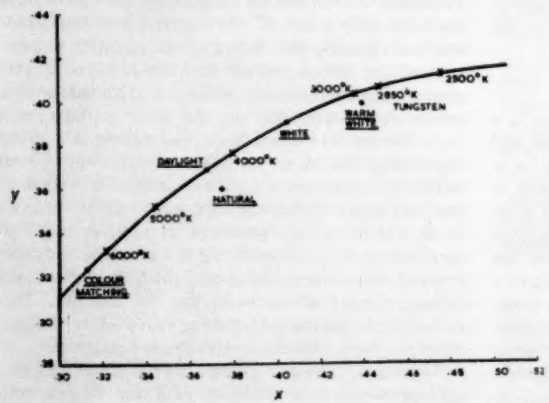
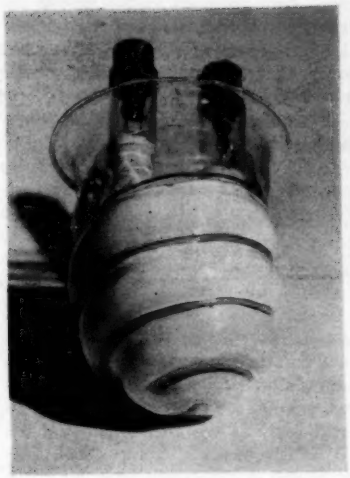


Fig. 6. Chromaticity values of fluorescent and tungsten lamps.



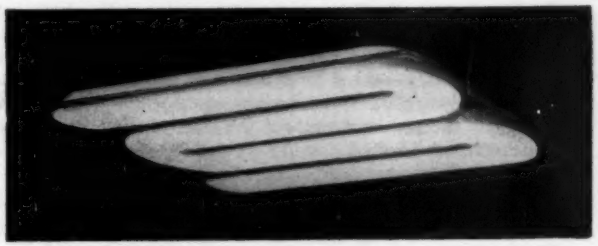


Fig. 7. Experimental compact fluorescent lamps.

watt tube had the highest loading of any fluorescent lamp in the world. The British 8 ft 125-watt lamp had the highest lumen output. It would have obvious advantages if, for example, the wattage of a 5 ft 80-watt lamp could be increased to some higher value without any reduction in life or efficiency. This is not simply a matter of increasing the current through the tube which causes a reduction in the tube voltage and requires a disproportionately large current increase to give the required high wattage; this adversely affects both life and efficiency.

In 1957 two highly loaded fluorescent tubes, one of novel design, were introduced in the U.S.A.[9,10] These designs take account of the well-known fact that high current density and high mercury vapour pressure both lead to reduced efficiency. Unduly high current densities are avoided in both types of lamp by keeping the tube voltage as high as practicable. In one type this is done by adding neon to the usual argon filling gas; in another type the tube cross-section is made kidney-shaped to bring the discharge into closer proximity with the tube walls. This reduces the effective diameter of the tube without affecting the surface area. Limitation of mercury vapour pressure is achieved by keeping a part of parts of the tube at a lower temperature than the main part. It is the temperature of this cooler region which, determines the vapour pressure and not the highest or average temperature of the tube.

The life and luminous performance of these and other highly loaded lamps which have been marketed in America and in Europe are poorer than obtained with normal tubes; it cannot be said that a fully satisfactory solution to the technical problems associated with high loading has yet been found. The technique of vapour pressure control brought out by these developments may prove to be of value as a method of increasing the tube voltage of the 5 ft 80-watt lamp; this tends to be lower than desirable particularly when the ambient temperature is high.

(2.6) Compact fluorescent lamps

Another method of making the source more concentrated is to make the long discharge path, which is an essential feature of the low pressure fluorescent lamp, follow a zig-zag or spiral course. This rather old idea is being revived, particularly in the U.S.A., where a flat fluorescent lamp has recently been announced[11] although it is not yet on the market. Fig. 7 shows an American lamp of this type, together with an early experimental British compact lamp, developed some years ago but never marketed because of its rather high manufacturing cost. The flat lamp is made from a mould-blown component having a depression of semi-circular cross-section defining the discharge path. This is closed by sealing a flat plate to it. as shown in the photograph. The British lamp is made from two mould-blown components, shaped so that when sealed together, one inside the other, a spiral path for the discharge is formed. In both designs the discharge path is some 3 ft long and gives about the same luminous output as a 4 ft 40-watt lamp. It is interesting to speculate whether the flat shape will enable the fluorescent lamp to make any impact on the domestic market which has hitherto relegated it to the kitchen or the garage.

(2.7) Low voltage cathodes

Some mention is needed of the trend, particularly in America, towards much smaller cathodes for fluorescent tubes.[12] This enables filament heating transformers used in starterless circuits to be made appreciably smaller and cheaper. It also results in a

slight gain in overall efficiency since less energy is required to heat the cathodes. Lamps with low voltage cathodes are interchangeable with the older high voltage cathode tubes in switch start circuits but not in all switchless start arrangements. For this latter reason it seems unlikely that the low voltage cathode will be adopted for the British 80-watt lamp

(2.8) Reflector lamps

The luminance of a fluorescent tube can be increased by silvering the back half of the tube. Some years ago it was proposed to use, instead of a metallic mirror, a coating of a white powder between the glass wall and the fluorescent coating.[13] A fluorescent lamp of this type was marketed in this country in 1956.[14] The reflecting surface is a thin coating of titanium dioxide which also reflects well in the ultraviolet. The reflecting coating is first applied over the whole tube and before the fluorescent coating is applied a strip of the titania coating, about one-third of the circumference in width, is removed. This serves as a window through which about 90 per cent of the light from the tube passes. Most of the remainder passes through the reflector coating. Fig. 8 shows the polar diagram of a typical reflector tube. Tubes of this type are finding useful application in dusty and dirty situations where it is difficult to keep the tube clean: a deposit of dust on the reflector causes much less loss of light than it would do on a normal tube. A recent report from the U.S.A. mentions a newly developed so-called aperture lamp which appears to be a form of highly loaded reflector tube. It is claimed that the luminance of the aperture is 22,000 foot-lamberts and it is expected to find use for bridge and tunnel lighting, floodlighting and even for automobile headlamps. There is insufficient information available to enable these claims to be judged.

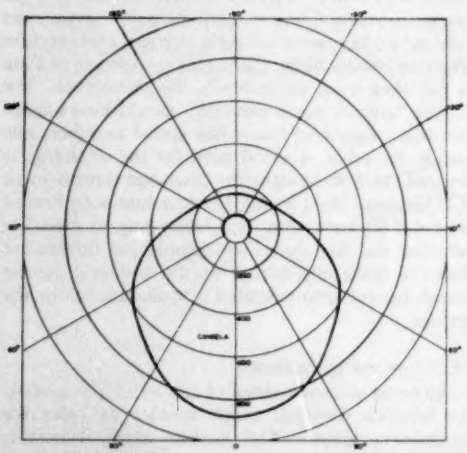


Fig. 8. Polar diagram of 5 ft 80-watt reflector tube.

(2.9) Circuits

The ordinary choke circuit with a switch to start the arc is still one of the cheapest arrangements for operating fluorescent lamps. Nevertheless, the presence of two consumable items in the circuit, the lamp and the starter, adds to the problem of maintaining the installation. Moreover, there is much evidence to show that the life performance in a well-designed switchless start circuit is greatly improved. Switchless start circuits are, therefore, growing in popularity, particularly as the cost differential between the two arrangements is getting less. This trend has been helped in this country by the introduction of the so-called universal lamp, which is suitable for both types of circuit.

Perhaps the most interesting new circuit development is the germanium transistor inverter for obtaining A.C. from a battery supply, which is particularly applicable to transport lighting. This development has been well described in a recent paper.[15] A new type of semiconductor device, the silicon controlled rectifier, is capable of handling much higher power and of operation from a higher D.C. voltage. It is perhaps not too much to hope that this type of semiconductor will be developed to operate in a frequency-changer circuit giving, say, a 10,000-cycle output from a 50-cycle input. Such an arrangement might make high frequency operation, with its attendant advantages of cheap, lightweight control gear, freedom from stroboscopic flicker and improved lamp efficiency, a practicable proposition.

(3) High Pressure Mercury Vapour Lamps

Increasing the mercury vapour pressure in a fluorescent lamp above the optimum value, which occurs at a temperature of around 40°C, adversely affects efficiency because of the reduction in the intensity of the important U.V. line at 2537A. If the electrical loading of a mercury discharge is increased to, say, 50 watts per cm. length of 25 mm. diameter tubing the tube wall reaches a temperature of about 600°C, and the mercury vapour pressure rises to several atmospheres if sufficient mercury is present in the tube. Under these conditions a much higher proportion of the energy in the discharge is radiated in the visible part of the spectrum and the luminous efficiency is increased by a factor of 8 to 10.

(3.1) Energy balance in an H.P.M.V. lamp

An examination of the energy balance in a 400-watt quartz H.P.M.V. discharge shows that about 16 per cent is emitted in the visible region and something like 23 per cent in the ultra-violet between 2,000 and 3,800 A.U. Only about 9 per cent is emitted by the arc in the infra red but about 38 per cent is lost by convection and conduction of heat from the arc tube; the remainder, amounting to 14 per cent, is lost at the electrodes. The principal factors affecting the luminous efficiency of the arc are mercury vapour pressure, arc length, arc tube diameter and the wattage loading. There is little room by varying these parameters for other than minor efficiency improvements, except under laboratory conditions.

(3.2) Fluorescent H.P.M.V. lamp

The most important developments in the H.P.M.V. lamp have been concerned with the utilization of the U.V. energy by means of fluorescence to improve colour and efficiency. There are no phosphors known which will withstand the temperature of an H.P.M.V. discharge tube. It is, therefore, necessary to apply the coating to the inside of a fairly large bulb surrounding the discharge envelope. Lamps of this description have been in use in this country since 1937 but the early phosphors gave only a rather small degree of colour correction. A number of phosphors having the desired temperature, excitation and emission characteristics are now available. The most important of these, magnesium germanate,[16] gives a remarkable emission in the red, a region in which the H.P.M.V. discharge is deficient, and a high degree of colour correction with little or no loss in luminous efficiency. A lesser degree of correction, but a gain in efficiency of perhaps 10 per cent, is obtained with strontium zinc phosphate,[17] which emits mainly in the yellow-orange region.

Magnesium germanate has a weak absorption band in the blue region and this tends to give the lamp a greenish appearance unless rather thin coatings are used. Attempts to compensate for this by using a tinted outer bulb absorbing in the middle region of the spectrum have been reasonably successful, but this subtractive method of correction involves a loss in efficiency.[18] At the relatively low levels of illumination usual in most streetlighting installations, colour discrimination is poor and some people appear to have difficulty in distinguishing colour corrected H.P.M.V. lamps from the uncorrected type. It is possible, therefore, that the main demand for the colour corrected lamps will be for streetlighting at fairly high illumination levels, such as are obtained at present with tubular fluorescent lamps, at places such as important shopping centres.

A modification of the usual colour corrected lamp has established itself in the U.S.A. and is finding some application over here. In this, the outer bulb is similar to the well known reflector bulbs in the tungsten lamp range. The fluorescent coating is applied on top of an internal vapourized metallic or powder reflector on the sides of the bulb. The bottom surface of the bulb is left uncoated but is etched to diffuse the light from the arc.

(3.3) Tungsten ballasted H.P.M.V. lamps

H.P.M.V. lamps have often been used in conjunction with tungsten lamps to improve the colour of the discharge or to eliminate the usual series choke, or for both reasons. When used in place of the choke the usual practice has been to mount the tungsten filament in the same outer bulb as the discharge tube. If it is intended to make a useful contribution to the light output and not merely to act as a ballast, the design of the filament is a matter of compromise, since it must withstand the high current during the run-up period of the discharge and have a life comparable with that of the discharge itself. A range of combined lamps of this description, in which the outer bulb is coated with magnesium germanate phosphor has been reported in the U.S.A.[19] These are 450-, 750- and 1,750-watt and are claimed to have initial efficiencies around 30 lm/w with a red ratio similar to that of standard illuminant C (full radiator at 6,500°K).

A study of this problem has shown the possibility of making an improved tungsten ballasted H.P.M.V. lamp using the new quartz tungsten iodine lamp discussed earlier.[20] The shape of the source is compatible with that of the discharge tube, which enables the two lamps to be placed in close proximity, giving rapid heating of the discharge and correspondingly short run-up time. For the same reason, good mixing of the light from the two sources is readily achieved. Also, the performance of the tungsten iodine lamp is much superior to that of a similar filament processed and operated under the unfavourable conditions inside the outer bulb. It is to be expected that this approach to the problem will lead to a tungsten ballasted H.P.M.V. lamp of excellent efficiency, colour and life.

(3.4) Colour modification of the discharge

Another method of modifying the colour of H.P.M.V. lamps is by the addition of zinc and cadmium to the discharge. Both these metals have an appreciable vapour pressure at the temperature of the bulb and each contributes characteristic arc

lines to the mercury spectrum. The blue emission from zinc, added to that of a fluorescent H.P.M.V. lamp, gives a colour not dissimilar to that of the xenon arc. Experimental lamps of this type were demonstrated recently[21] but because of zinc attack on the quartz envelope cannot yet be regarded as practical sources.

(3.4) Pulsed H.P.M.V. lamp for ciné projection

An interesting new H.P.M.V. lamp for ciné film projection was announced last year.[22] This comprises a water-cooled high pressure mercury lamp having an arc length of 17 mms. in a quartz tube about 5·5 mms. in diameter. The quantity of mercury in the lamp is restricted to a small controlled dose which is practically all vapourized when the lamp is in operation. The discharge is pulsed in synchronism with the moving film so as to give three short-period flashes, each of about 2·5 milliseconds duration, per frame. No shutter is required in the projector. Thus at 24 frames per second the lamp is flashing at a frequency of 72 per second, which ensures a reasonable freedom from flicker. The peak current per pulse is about 15 amps and the mean power consumed by the lamp is 800 watts; the luminous flux on the screen equals that of a 60-amp carbon arc. Because of the very high instantaneous loading the spectrum of the emitted light contains a high proportion of continuum and the source is stated to be excellent for projecting colour film.

(4) Sodium Lamps

The sodium lamp is one of the earliest of the hot cathode lamps. Much of the basic development work was done in Germany and the U.S.A. before the war. No significant use of the lamp has been made in the latter country, no doubt partly due to the poor design of lamp evolved to suit their series system of streetlighting.

The chief attraction of the sodium lamp is, of course, its high luminous efficiency and there are considerable improvements to report. The theoretical maximum efficiency of the sodium vapour discharge is certainly greater than 300 lm/w so that there is still scope for further gains. It is safe to assume that the final word on the subject has not yet been said.

(4.1) Lamp with dewar flask for heat conservation

The familiar 140-watt lamp has an arc length of about 80 cms. in a 1·8 cm. diameter tube. The tube is made U-shaped for compactness and is filled with about 10 mms. of neon containing a small amount of argon to assist starting. It also contains globules of metallic sodium distributed throughout its length. The vapour pressure of the sodium is very low when the lamp is first switched on and the neon spectrum predominates in the discharge. This gives way after ten minutes or so to the characteristic yellow glow of sodium when the tube warms up. To enable the arc tube to reach the required temperature of about 300°C, it is necessary to prevent, as far as possible, loss of heat by convection and conduction. Until a few years ago this was done by operating the arc tube inside a highly evacuated double-walled dewar flask. Three other ratings, 45-,60-and 85-watt, are of similar construction.

(4.2) Integral construction

After a long period of stability the past few years have seen much development in sodium lamps. This has been confined entirely to this country and Europe and may be said to have begun with the development over here of the now well-established integral lamp, in which the detachable dewar flask is replaced by a single-walled tubular jacket, into which the discharge tube is permanently sealed, and the jacket highly evacuated.[23] The limbs of the U-tube are fitted with glass sleeves before sealing in, which help further with the conservation of heat from the discharge. Elimination of the dewar flask in the integral construction simplifies installation, cleaning and replacement of lamps. The discharge tube is completely protected from the atmosphere and difficult starting under conditions of high humidity is eliminated, as is the problem of deciding when to renew the dewar flask, which gradually deteriorates with use. For these reasons, and because the more effective heat conservation makes possible higher luminous efficiency, it seems likely that the integral lamp is here to stay and that all sodium lamps will be of this construction within a few years.

(4.3) High wattage integral lamp

Other ratings of integral lamps have more recently been proposed. The first high wattage type to be marketed in this country consisted of two 140-watt U-shaped discharge tubes sealed into the same outer jacket.[24] Heat-reflecting sleeves are not required with this construction. The lamp has the same external dimensions as the 140-watt integral lamp, but is fitted with a stout 4-pin cap and each inner may be operated independently of the other. In yet another design the two 140-watt U-bends are placed end-to-end in a long tubular envelope.[25]

A complete break-away from the existing design of discharge tube has been made in one design. rated at 200 watts, which uses a straight arc tube of non-circular cross-section with lengthwise grooves or depressions separated by short lengths of tube of circular cross-section after the manner of the American 'Power Groove' fluorescent tube.[26] The lamp is capped at each end with bipin fluorescent

lamp caps, which enable the filamentary cathodes to be preheated in a starting switch circuit or by a filament heating transformer.

(4.4) Sodium resistant glass

Because of the intense chemical activity of hot sodium vapour it is necessary to use a special glass for the discharge tube which will withstand attack by the vapour. It is usual for this protective glass to be applied as a thin flashing on the inside of an ordinary glass tube. Sodium resistant glasses are of two main types: those which absorb sodium and those which do not. The absorbed sodium shows as a dark film on the surface of the glass which causes some loss of light. On the other hand, this film provides a uniform supply of sodium vapour throughout the length of the discharge tube and effectively overcomes the tendency to local sodium starvation due to mechanical and thermal movement of the sodium during operation of the lamp. Moreover, the absorbed sodium appears to reduce the loss of argon from the gas filling which occurs during operation of the lamp and which, if allowed to proceed too far, results in failure due to the inability of the lamp to start. It is possible to delay the effects of thermal movement or migration of the sodium in non-absorbing glasses by modifications to the cross-sectional shape of the discharge tube. The effect of clean-up of argon can be reduced in some measure by adjustment of the filling gas composition and pressure, but neither sodium migration nor gas clean-up in non-discolouring resistant glass have yet been wholly overcome.

The early integral lamps used, and continue to use, glass of the first type which, although not giving the highest initial efficiency, is substantially free from sodium migration and argon clean-up troubles. The newer types of integral lamp use the second type of resistant glass and are achieving improved initial efficiencies. (See Table 2.) Much more experience will be required to decide which type of glass will give the best overall performance.

(5) Xenon Lamps

The light from a high current density discharge in xenon has a spectral distribution similar to that

Table 2

Luminous data for sodium lamps

Type	Watts	Initial lumens	Average lumens (4,000 hrs. life)
U-bend	45	2,610	2,250
with	60	4,020	3,420
Dewar	85	6,200	5,525
Jacket	140	10,200	9,100
U-bend	45	2,650	2,295
with	60	4,120	3,540
Integral	85	6,800	5,950
Jacket	140	11,200	9,800
	280*	25,200	22,400
Linear with Integral Jacket	200	20,000	18,400

* Double U-bend lamp

Table 3

Characteristics of xenon lamps

Data for short-arc, air-cooled lamps:			
Input (watts)	500	1,000	2,000
Approx. operating current (amps)	28	57	112
Approx. arc length (cms)	0·28	0·28	0·35
Arc width of 10 per cent axial brightness (cms)	0·26	0·30	0·42
Arc luminance at centre of arc (stilb)	15,000	25,000	25,000
Bulb diameter (cms)	4·1	5·0	7·0
Data for high wattage, long-arc, air-cooled lamps:			
Input (kW)	20	65	
Operating current (amps)	75	250	
Arc length (cms)	190	240	
Tube diameter (cms)	3·0	5·0	
Lumen output (lumens)	560,000	1,940,000	
Luminous efficiency (lm/w)	28	30	

of a full radiator at a temperature near 6,000°K. Much of the early development work on xenon lamps was done in this country,[27] but most of the recent work has been done abroad, particularly in Germany.[28] Xenon lamps are costly to manufacture and because of the high ratio of starting to running voltage require rather bulky and expensive control equipment. Despite their excellent colour characteristics the lamps have, for these reasons, not come into widespread use.

(5.1) Types of lamp and performance

Development has followed two main lines: the short arc length, high luminance type, and the long arc length, relatively low luminance type. The former, which are used mainly for optical projection work, may be filled to a xenon pressure as high as ten atmospheres measured at room temperature. The long arc length lamps are usually filled to a fraction of an atmosphere pressure and are used for general lighting.

Short arc length, air cooled, high pressure lamps are available from 160-watt rating up to 2½-kW. The higher wattage compact source types are used mainly for film projection, both black and white and coloured, which has been, until recently, the only really important application for xenon lamps. A British 2-kW lamp for 16 mm. and 35 mm. film projection is now available.[29] It is filled to four atmospheres cold, corresponding to ten atmospheres when in use, has an arc length of 8·5 mms. and an average arc luminance of 25,000 stilb. The 160-watt lamp has found some application in Germany for colour matching. The long arc length lamps are used mainly for stage and other special lighting applications and their use appears to be on the increase. Lamps of 6,-10,-20-and even 65-kW rating are available on the Continent. The latter lamp uses a quartz tube 8 ft long and 2 in. in diameter; it operates at a current of 250 amps and has an efficiency of 30 lm/w. Such a lamp must necessarily have limited application. One of the most spectacular installations is that in a square in München, comprising three 20-kW lamps mounted on a column 100 ft high. The total luminous flux from the lamps amounts to $1{\cdot}6 \times 10^6$ lumens and the average illumination is 10 lm/ft² over the square. Table 3 gives the main dimensional and other characteristics of the 20-and 65-kW xenon lamps.

Much work has yet to be done on these interesting sources to simplify their manufacture and operation and to make them more acceptable for general lighting applications. It is at least uncertain whether this type of source could, for general lighting purposes, ever seriously compete with the simpler and cheaper tungsten filament lamps, with their warmer colour and comparable luminous efficiency.

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Discussion

DR J. W. STRANGE: I wish to start by thanking Mr Jenkins not only for an excellent paper as circulated before the meeting but also an excellent lecture and some very interesting demonstrations.

On tungsten lamps he has referred to the increase in bulb temperatures and the reduction in lamp sizes. I still feel that this move is one that has to be watched with great care, and I am doubtful whether it has been a wise alteration. The point that has too often been forgotten is that there are many fittings

in use designed with sufficient margin only for the larger lamps previously manufactured, and by going to small lamps the dangers of overheating are considerable. I feel that this Society is the right body to take an overall view of this problem and advise lighting engineers of the need for caution.

Another point requiring caution, to which Mr Jenkins has referred, is the fluorescent lamp with the low voltage cathode. I wish to stress that if it does come on to the British market it will need to be treated with care. There is a real danger that such low voltage cathodes cause overheating of filament heating transformers used with the high voltage cathode.

Coming now to the new products, probably the most interesting is the tungsten iodine lamp in a quartz envelope. One aspect of particular interest is once again the long period between the original idea and its commercial application. Many changes in techniques since Langmuir's original work in 1915 have made this possible. The problem of controlling the iodine cycle is one of considerable interest and it is apparent that great progress has already been made. I have some doubts about the experimental 12 V 100 W lamp shown in Fig. 3, where the quartz envelope is apparently in direct contact with the cap. As I understand it, the minimum temperatures at which such lamps run are about 270°C, and maintaining adequate temperature control in such a lamp would appear to be much more difficult than in the symmetrical tubular lamps.

In his reference to fluorescent lamps Mr Jenkins has left me rather dissatisfied in his references to the 'natural daylight' lamp. It is uncertain whether he is referring to a lamp similar in spectral energy distribution to that of natural daylight or one having the same colour appearance. The references under (2·2) are too vague to please either a physicist or the lighting engineer. It would be interesting if he could hazard a more definite forecast of what the future efficiency of these lamps might be. The reference to the advantages which followed the use of classified phosphors is somewhat misleading, both in Mr Jenkins' paper and in the American papers referred to. This is particularly so of the reported gain of 10 per cent in efficiency. In my view the achievement of high efficiency starts with the preparation of the raw materials and it is only by careful control of these that the inert small particles apparent in his slides can be avoided. In a correctly manufactured phosphor the gains to be achieved by classification of the final product are much smaller than the 10 per cent referred to.

The de luxe natural tube referred to under (2·4) is a surprising case of a lamp which started as a very modest trial and has had quite outstanding success. In part it owes this to the poor quality of some of the lamps on the market alleged to be 'natural' and in the high fidelity class. This lamp is an example of the widening gulf between the high efficiency lamp and the true high fidelity lamp.

The development of the linear 200 W sodium lamp is a most interesting feature of the last year or two. In the comparisons given in Table 2 I was a little puzzled by the relative figures for the 200 W and 140 W lamps, and the double U-bend or 280 W lamp. I would be interested to know whether the overall efficiency including ballast losses for these lamps makes any marked difference to the overall efficiency. I am also particularly interested why the lumen output figures for the 280 W combination is more than double that for the 140 W lamp. Finally, I was very sorry to see again the so-called compact fluorescent lamp. When it was first shown some years ago I thought it was a mistaken line of development and I still think so. The fluorescent lamp should develop along its own lines and not attempt to imitate the incandescent lamp.

I should like to finish by quoting from a lecture given in 1891 by our first President, Silvanus P. Thompson, which is very relevant to our discussion today. He said: 'We appear to be within measurable distance of the invention of a new kind of artificial lighting. The luminescent lamp of the future, whatever its shape or tint, will be one giving a pure and a cold light that will not poison the air with fumes of combustion, nor overheat it with wasted calorific vibrations.'

MR H. R. RUFF: Reference is made to the improvement of the colour rendering properties of fluorescent lamps. Before the 'daylight' lamp was introduced in 1942 subjective tests had shown a preference for a spectral distribution approaching sunlight for the general appreciation of colours and recent tests have confirmed this.

During fluorescent lamp developments, lamps similar in appearance to sunlight and incandescent lamp light have been made with different spectral distributions, one giving reasonable colour rendering with high luminous efficiency and the second with improved colour rendering with correspondingly lower efficiency. For installations at the same light intensity there is unanimous preference for good colour rendering. If one installation provides 25 per cent more light at the sacrifice of some colour rendering the choice is much less definite, even at intensities of 50 lm/ft². It seems that for the true appreciation of colour, high intensities are really required and I would welcome Mr Jenkins' comments on this.

In paragraph (4.4) he states that sodium migra-

tion in non-discolouring sodium resistant glass has not yet been wholly overcome. Our experience with the grooved linear sodium lamp is that by designing so that the temperature difference from the point of the groove to the main discharge is greater than differences along the lamp, the migration has been slowed down to such an extent that it is no longer a factor in the useful lamp life.

DR H. H. BALLIN: Experiments carried out recently in a large chain store have shown that the replacement of higher efficiency tubes by the new 'de luxe Natural' tubes, although leading to a reduction in lighting levels, meant, in fact, a considerable improvement in the appeal of the wares on show, as long as the illumination was not below 30 to 40 lm/ft^2. The use of de luxe tubes in this country and in the United States is relatively small but in Germany a very much higher proportion of fluorescent tubes are of the de luxe kind. Perhaps we have now reached the point where further improvements should be in quality rather than in quantity of light.

I am surprised that the author showed an experimental fluorescent tube with a colour rendering similar to a low voltage tungsten lamp. The tungsten lamp is by no means a perfect light source and one of the great advances in recent years is that fluorescent tubes have been developed which combine the best of the tungsten lamp, i.e. the excellent red rendering, with the best of daylight, namely, good white and blue rendering.

The examples of tungsten lamps with 'fancy shapes' are interesting but must be treated with caution as the multiplication of types could cause chaos, not only for the manufacturer, but also for the distributor. In any case the bare bulb must be considered undesirable from the brightness point of view and standard bulbs, if necessary in specially shaped lighting fittings, would be preferable.

MR B. C. OSSITT: I hope the idea of making tungsten lamps generally of smaller overall size is not going to build up trouble through local heating in the lampholder, fitting and in particular flexible cables. My own Board has been testing the effect of the heat generated by these smaller lamps and there appear to be very few cables on the market today which will stand up to the high temperatures generated. It may be that the sale of such lamps will cause lots of trouble particularly in domestic premises where wiring generally is of some age. Consumers should be advised not to use these lamps unless they are certain their house wiring and in particular the lamp flexibles and lampholders are in good condition. In our own testing house during accelerated tests with these smaller dimensional lamps, the ordinary twin maroon flex deteriorated very quickly indeed.

MR F. WIDNALL: I would like to add to the discussion on the question of tungsten lamps and the size of the modern bulbs. It is true that the reduced size of the bulbs is a problem to the fittings manufacturers and to users. I have a good deal to do with the size of the fittings and I sympathize, but I am not in agreement with Dr Strange's view that it should be viewed with suspicion. We must remember the world-wide usage of lamps and this change is well under way in America and Europe, and it is clearly allied to a general movement to miniaturization. There is a definite tendency today to make everything smaller if you possibly can. You are therefore left with the problem of trying to cope with the situation as it exists.

In 1929 there was an ERA report issued on the heating of lighting fittings, and of all the fittings tested, about 80 per cent overheated the cable, so there is nothing new about overheating. There has been a tendency to exaggerate the heating problems because there is no definite datum line from which to start.

I would like to ask Mr Jenkins if he has any information on the spread of temperature readings likely to be experienced in a series of tests with production lamps, compared with a test with a heat test source for a range of similar fittings. If the heat test source needs to provide a large margin of safety because of the wide spread of results to be expected with production lamps and fittings, it will embarrass the fittings maker.

However, although manufacturers of fittings and perhaps users are nervous of the newer small lamps, they are with us and have come to stay.

MR R. J. FOTHERGILL: Reading Mr Jenkins' paper made me cross; listening to him I have become more friendly. Firstly, I was cross because of the opening paragraph in which the author says the tungsten lamp has 'simplicity, cheapness and excellent colour rendering'. Yet most of the discussion up to now has been about the complications of using modern small-bulb lamps. Their cheapness is a myth; true their first cost is low but it must be remembered that the purchase of a lamp also represents a potential expenditure on electrical energy many times the retail price of the lamp. In practice our nominal 1,000-hour life lamps are only allowed to last about 750 hours and the labour cost of lamp changing may be almost any sum from 6*d*. to 30*s*. I am not suggesting there is anything wrong with the quality of present-day GLS lamps; it is simply that life is a product of quality of manufacture and

quality of electricity supply and the latter cannot be all that is necessary for maximum life.

The claim of colour rendering is also false. Of all the common light sources only the deluxe warm white tubular fluorescent lamps create conditions which appeal to most people when the colour rendering properties are being properly examined. I once had occasion to show the effects of the six 'white' tubular fluorescent lamps and that of silica diffused tungsten filament lamps to seven university professors. Without exception they behaved exactly as all the other persons who had performed this experiment. On considering the appearance of their hands they chose de luxe warm white. Of course, some of them were unhappy when they realized they had approved something other than filament lighting but surely this confirms my dissatisfaction with Mr Jenkins' statement. Perhaps he might change it to read 'satisfactory colour rendering' or 'acceptable colour rendering.'

If I take a cardboard cylinder, paint it with fluorescent paint and shine a black lamp on it surely I have a 'fluorescent tube'. Why then should this name be given to proper light-producing devices which are basically 'lamps'? Let us agree that these long things be called fluorescent lamps and not fluorescent tubes. In Mr Jenkins' paper on page 3 the heading is 'Fluorescent Lamps', but reading on shows confusion in the use of these two names. Ours is a cultural society and I think the least we can do is to use proper names to describe our essential tools.

As usual with lamp papers we are subjected to the glamour and wonder of the large variety and numbers of types produced but it is impossible to find a compact long-life source with good colour rendering which will operate in accordance with the electricity supply. Two 12 in. 8 W tubular fluorescent lamps have to be used to replace a 240 W 60 W filament lamp; to replace a 110 V 100 W lamp three 18 in. 15 W tubular fluorescent lamps have to be used—the inconvenience is obvious. The complete answer does not lie in the use of MBF/U lamps which are not accepted by many engineers because of their possible extinction by voltage depressions. Is there hope for any solution to these essentially practical requirements appearing soon?

THE AUTHOR (in reply): I wish to thank all those who added to the interest of the paper by taking part in the discussion.

I fully agree with Dr Strange that this Society is the right body to take an overall view of the old problem which the reductions in bulb dimensions of GLS filament lamps has brought into the open. This is a matter which concerns the lamp maker, the fittings designer, the lamp holder and cable manufacturers as well as the user. I do not think responsible fittings suppliers need cautionary advice; has it always been possible to overheat fittings by improper use and it may be that smaller bulbs will give the thoughtless or the careless more scope. Much can be done to reduce this risk to something quite small by clear marking on the fitting itself of the maximum wattage for which it is intended. It seems to me that the real danger arises from the cheap, inflammable shades with which the market is flooded and that it is here the situation needs careful watching.

As stated in the paper, I think it unlikely that low voltage cathodes will be used for the British 5 ft. 80 W lamp. Their use in this country for the international 4 ft. 40 W lamp merits serious thought.

No part of the bulb of the experimental 12 V 100 W projector operates below the critical temperature for the iodine cycle. Even if this were not the case, it does not mean that the cycle would not function, provided the cool region in question would not normally receive tungsten by evaporation.

Colour appearance of white fluorescent tubes is of little significance in efficiency discussions; the maximum efficiency calculation mentioned in the paper was for a lamp giving a spectral distribution similar to that of one of the phases of natural daylight. The corresponding figure for a spectral distribution similar to the international cool white colour is about 30 per cent greater, or say 80 lm/W.

The gain in efficiency due to classification applies to phosphors as they are made at present and not to ideal phosphors which may arise in the future and for which classification would give no improvement.

I ought perhaps to have made it clear that the luminous performance data for the 280 W (double 140 W) sodium lamps refer to lamps made with an improved non-discolouring sodium resistant glass. This glass shows more tendency to sodium migration in the 140 W lamp, which accounts for the somewhat poorer efficiency of the single lamp.

The 200 W linear lamp is, as Mr Ruff has pointed out in his comments on the paper, relatively free from sodium migration effects and operates well with non-discolouring glass. In addition, because of its special design, the lamp appears to have an intrinsic efficiency some 20 per cent higher than that of the U-shaped lamp as it is made at the present time.

The efficiency figures quoted are for the lamp alone, as is usual practice. Overall efficiency may be as much as 20 per cent below these figures, depending on the losses in the control gear.

I cannot, myself, see anything technically or aesthetically questionable in bending a tubular source into a more compact shape. I feel confident that if

the fluorescent lamp is to make any serious impact on the domestic market it must develop along compact lines.

I was interested in the quotation from Silvanus Thompson's biography. Experience has, however, shown that at economically acceptable levels of illumination, a warm light is preferable to a cold.

Mr Ruff refers to the effect of illumination intensity on colour appreciation, and suggests that for the true appreciation of colour high intensities are required. One ought, I think, to differentiate between social and industrial or commercial applications. For the former there is no doubt in my mind that the colour characteristics of a black body emitter or something close to it, such as a tungsten filament lamp, at a temperature lower than 2,800°K is generally preferred. For the latter application relatively high colour temperature is acceptable provided the illumination level is adequate and the colder the colour the higher the intensity preferred. For still colder light of the type used for accurate colour discrimination in industry, illumination levels of the order of 150 lm/ft^2 or higher seem to be preferred.

I agree with Mr Ruff that the onset of sodium migration in sodium lamps made with non-discolouring resistant glass can be delayed by modifications to the cross-sectional shape of the discharge tube and this is stated in the paper.

Dr Ballin appears to confirm Mr Ruff's contention about de luxe colour fluorescent lamps so perhaps we may expect a marked change in the habits of the users of fluorescent lamps. I doubt it myself. I have long held the view that temperature radiation provides the most acceptable form of light and the filament lamp is the most convenient artificial light source. It is perhaps not sufficiently appreciated that it is technically possible in a fluorescent lamp to achieve something very close to the spectral distributions of both low and high temperature filament lamps with the advantage of improved luminous efficiency.

I sympathize with Mr Ossitt in his problem. There is little I can add to my comments on Dr Strange's remarks. I think the situation to which Mr Ossitt refers has existed for a long time and while the bulb size reductions certainly have not improved matters, it is probably true to say that they are not the root cause of the trouble. There is no doubt in my mind that this Society, by promoting discussion between the various interests, can make a valuable contribution to the solution of the problem.

I agree with Mr Widnall's remarks on the bulb size reductions and the heating of lighting fittings and I thank him for expressing them so clearly for the record.

A large number of temperature measurements have been and are being made in fittings of various types and it is certainly the intention of my own company to make these kind of data available in due course. One would expect that the spread in temperature rise readings in free air taken at the lamp cap on a batch of heat test sources might be of the order of ± 5°C and that of a batch of production lamps, say, ± 10°C. Measurements in a typical fitting show that the spread in temperature rise tends to be, if anything, smaller than in free air; it seems reasonable to assume that, in general, the spread in fittings will not differ greatly from that in free air.

Mr Fothergill does not accept my description of the tungsten filament lamp as simple, cheap and of excellent colour rendering. This is a pity and there is little I can do about it. No doubt Mr Fothergill and the seven university professors to whom he referred have now replaced all the filament lamps in their houses by fluorescent tubes, or should I, with Mr Fothergill, call them tubular fluorescent lamps?

UDC 621.329

Plastics, Yesterday, Today and Tomorrow

By C. L. CHILD, B.Sc., Ph.D., A.P.I.

Before looking at the current developments which are taking place in plastics technology, it is well to have our feet firmly planted on the ground by taking a quick look at what has happened in the past. We shall then be better able to appreciate the accelerating rate of development at the present time.

The group of materials known as 'plastics' is hard to define both unambiguously and comprehensively, but much easier to describe. Although the number of plastics theoretically possible is unlimited, at the present time about a score are of commercial importance.

The properties which plastics have in common and which enable us to group them together as a single class of materials of construction are these:

(1) Plastics are synthetic, of high molecular weight and with complex molecules.

(2) Plastics are usually organic chemicals, though at the present time there is the important exception of the silicone family which is essentially based on the inorganic element silicon, whilst other inorganic plastics are on the horizon.

(3) Plastics are sensitive to temperature and at some period in their history there is a temperature at which they can be made to flow in a controlled manner under applied pressure. Some retain this property throughout their history; others, having reached this temperature, undergo a chemical change and become infusible.

(4) Plastics have limited temperature ranges of usefulness, becoming more brittle as the temperature decreases, softer as it rises. The lower limit may be minus 100°C. or even much lower; the upper limit never exceeds (at the present time) 350°C. and generally lies in the range 70 to 90°C.

(5) Plastics are of low specific gravity—generally in the range 0·9 to 2·5.

(6) Plastics have mechanical strengths approaching those of metals measured on a strength to weight basis, but much lower stiffness.

(7) Plastics are electrical insulators.

(8) Plastics have low thermal conductivity.

(9) Plastics are generally resistant to inorganic chemicals, but in general are attacked or dissolved by organic chemicals.

This general description shows that there are no clear-cut dividing lines between, on the one hand plastics, and on the other fibres and textiles, or rubbers, or paints and varnishes, or adhesives. It is this overlap that is responsible for the difficulties in defining the term 'plastics'.

Leaving aside such well-known plastics materials as bitumen, gums, shellac, horn, glass and natural rubber and concentrating on those synthetic materials which are commonly known as plastics, it can be said that plastics technology is only now just about a hundred years old. The story starts with the independent discovery at about the same time in America and in this country of nitro-cellulose, most commonly known under the trade name of 'Celluloid'. The remarkable advantages and properties of this material won it early recognition in both countries. It will be recalled that the discovery of 'Celluloid' in America was accomplished by the Hyatt brothers, who won a large money prize for the invention of a synthetic material from which billiard balls could be made, but it is perhaps not so well-known that the first commercial exploitation of their invention was in the manufacture of dental plates, and not in the manufacture of billiard balls. It is indeed interesting to reflect that the plastics industry demonstrated its versatility right from its birth.

The advantages and disadvantages of nitro-cellulose are well-known, and it is not surprising that strenuous efforts were made to produce another material which had the same advantages of toughness, ease of working and dimensional stability but did not suffer from the disadvantages—particularly the near-explosive inflammability of the material. Though it is true that Cross and Bevan did discover cellulose acetate towards the end of the nineteenth century, no real progress was made until after the first world war, as their invention, while technically satisfactory, suffered from the drawback of its very high price. The manufacture of cellulose acetate dopes for aircraft during the first world war ensured the supply on a substantial scale of cellulose acetate materials at a reasonable price after the war, and cellulose acetate moulding materials made their appearance on the market in the early 1920s.

These materials overcame the inflammability risk of nitro-cellulose but were not so tough or so dimensionally stable. They were easy to work and brought with them a new technique for fabricating plastic materials, namely injection moulding, which is a modification of the pressure die-casting technique used with metals. As cellulose acetate was not with-

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BASIC NATURAL PRODUCTS	INTERMEDIATE STAGE MATERIALS	CHEMICAL RAW MATERIALS	
		Phenol	1
		Phenol derivatives	2
		Cresol	3
		Benzene	4
Coal	Coal tar	Phenol	1
		Adipic acid	5
		Hexamethylene-diamine	6
		Terephthalic acid	7
Water			
Coal	Calcium carbide	Acetylene	8
Lime	Nitrogen	Melamine	9
Air			
		Methanol	10
Coal		Formaldehyde	11
Water		Carbon monoxide	12
		Phosgene	13
Coal		Hydrocyanic acid	14
Water	Ammonia	Nitric acid	15
Air		Urea	16
Agricultural products	Crude butyric acid	Butyric acid	17
	Crude cellulose	Cellulose	18
	Ethyl alcohol	Acetic acid	19
		Chloroform	20
		Acetone	21
		Ethylene	22
		Ethylene oxide	23
Petroleum	Oil cracking products	Ethylene glycol	24
		Propylene	25
		Butadiene	26
		Benzene	4
		Styrene	27
Salt	Hydrogen	Hydrogen chloride	28
Water	Chlorine	Chlorine	29
Fluorspar		Hydrofluoric acid	30

Condensation reaction

CHEMICAL REACTIONS	POLYMERS
1+11	Phenol formaldehyde
16+11	Urea formaldehyde
9+11	Melamine formaldehyde
24+7	Polyethylene terephthalate
5+6	Nylon
13+2	Polycarbonates
18+15	Cellulose nitrate
18+19	Cellulose acetate
18+19+17	Cellulose acetate butyrate

Polymerization reaction

PRELIMINARY CHEMICAL REACTION	MONOMERS	POLYMERS
	22	Polythene
	25	Polypropylene
8+28	Vinyl chloride	Polyvinyl chloride
21+10+14	Methyl-methacrylate	Polymethyl-methacrylate
	27	Polystyrene
20+30	Tetrafluoroethylene	Polytetra-fluoroethylene
8+29	Vinylidene chloride	Polyvinylidene chloride
	26+27	Butadiene-styrene copolymer
	26+Methyl-methacrylate	Butadiene-methylmethacrylate copolymer
26+(8+14)	26+Acrylonitrile	Butadiene-acrylonitrile copolymer

Fig. 1. Derivation of some plastics.

out its faults, the attraction of making plastics by the simple (or relatively simple) chemical modification of the ready-made cellulose molecule from nature has tempted chemists to make yet other cellulose plastics. The most successful of these which are on the market today are cellulose propionate, cellulose butyrate, and cellulose acetobutyrate. With each development there has been a gain on the swings and a loss on the roundabouts, but each of these materials has its place in industry.

At this stage we can go back in time to about 1907 when that genius of industrial chemistry, Leo Baekeland, did his famous work on controlling the very well-known reaction between phenol and formaldehyde, and produced as a result the first phenolic resins, which have become so widely known throughout the world as adhesives, varnishes, and the resin constituent of the best known of all thermosetting moulding powders. The first world war, and the arrival at about the same time of the motor car and aeroplane, gave a great spur to the establishment of these thermosetting resins and moulding powders, but once again they were not without blemish. Unfortunately, when thermosetting resins are made from phenol and formaldehyde they are always dark in colour. The advantages of bright, clear colours for decoration and identification promoted a demand for thermosetting plastics with the properties of phenol formaldehyde materials but with no colour limitations. In the mid-1920s a step towards satisfy-

ing this demand was the discovery of the urea-formaldehyde resins and moulding powders in Europe; later still, in America were developed the melamine-formaldehyde resins and moulding powders, which, apart from their cost, have most of the advantages of both the phenolic and the urea materials.

The development of phenol and urea plastics and of the cellulose plastics had firmly established the plastics industry in the industrialized countries. This led to a search for new materials on a much wider front than before, and chemists started to make many kinds of long molecules. As a result the wholly synthetic plastics with which we are most familiar today began to make their appearance. It would be tedious to trace the history of all of them, but in the late 1920s there appeared polyvinyl chloride and co-polymers of vinyl chloride and vinyl acetate, in the early '30s came polythene and polymethyl methacrylate, in the mid-1930s came nylon, and in the early 1940s polytetrafluorethylene (or p.t.f.e. for short). Today, leaving aside individual grades and minor modifications of basic chemical materials, there is, as has already been said, something like a score of different plastic materials in commercial production throughout the world.

The plastics themselves have been manufactured from the basic materials—coal, lime, air, water, salt, etc.—in an essentially random, hit-or-miss manner (Fig. 1). For example, we have taken vinylchloride nonomer and have instructed it to polymerize, that is, for one molecule of vinyl chloride to join on to another, and so on, and thus build up a long chain. We have, over the years, become adept at making this reaction occur without serious risk of explosion or fire, and we have felt rather pleased with ourselves because we have been able to control the average molecular weight of our product and also the molecular weight distribution in any individual instance. When considering how clever we were in doing this it was always a sobering thought to remember that we could not tell the molecules whether to join head to head or head to tail, or whether to orient their pendant groups or atoms in any particular direction (Fig. 2). It was here that probability took control. All we could do, until a few years ago, besides controlling the molecular weight and the molecular weight distribution, was to control the chemical constitution by appropriate choice of our initial reactants. When we were making, for example, a co-polymer of vinyl chloride and vinyl acetate, we could ensure that on the macroscopic scale the final product had a predetermined ratio of vinyl chloride to vinyl acetate radicals in its composition, but we could not control the order in which these radicals joined a given molecule (Fig. 3).

The fact that most plastics are organic materials is a natural consequence of the fact that carbon joins to itself so very readily that it provides the easiest starting point for building up very large and long molecules. However, the sheer necessity of obeying the laws of thermo-dynamics places limitations on the thermal resistance properties of plastics based upon carbon, and in time research was devoted to looking

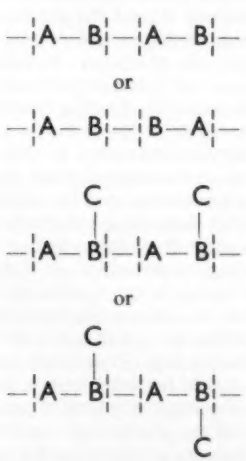


Fig. 2. Possible arrangements of monomer units in a polymer molecule.

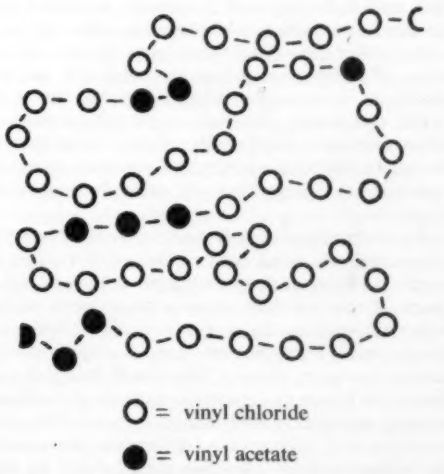


Fig. 3. A random copolymer of vinyl chloride and vinyl acetate.

at inorganic polymers, which may be expected to withstand very much greater temperatures. The first commercially successful answer to this problem has been the development of the well-known silicone plastics based on a back-bone of silicon and oxygen.

There are ninety-two elements in nature—in this connection it is unnecessary to worry about trans-uranium elements made in the laboratory in recent years—and the number of permutations and combinations open to us in making either organic or inorganic, or even mixed organic/inorganic polymers would send the most hardened football pool addict into a frenzy. We must be thankful that up to the present our chemists have restricted their attentions to a relatively small number of elements—mainly carbon, silicon, oxygen, nitrogen, chlorine, fluorine and hydrogen.

The story thus far brings us up to about 1955, and to consider what has happened since then, and is happening now, we can divide the field into two phases, (1) developments in materials, and (2) developments in processes.

Developments in Materials

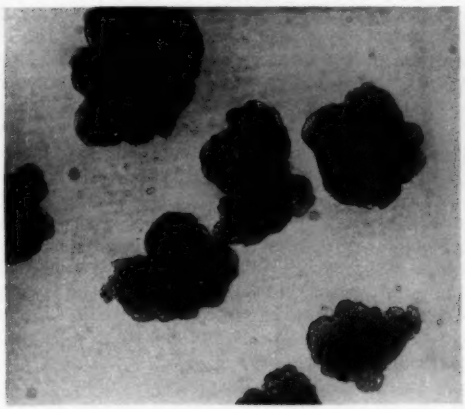
The first line of development in the last few years has been a continuation of the same broad stream of development as has been followed during the last hundred years—namely the development of new chemical formulations. In particular, during the last few years, there have been announced the polycarbonates, polyformaldehyde, polyethers, polyurethanes and polypropylene. These new materials all take advantage of readily available raw materials, and each is finding uses in industry dictated by the particular combination of properties which it, and it alone, offers. In saying this it must be stressed that none of these plastics has exhibited any startling deviation in properties from the properties of the older established materials; each differs from all other plastics in degree rather than in kind, and it is the subtle differences achieved that make a particular material fitted better than any other for a particular purpose.

Undoubtedly, one of the most interesting branches of research which has been carried out in the last few years has been work on inorganic polymers, but as much of this has been done in government laboratories throughout the world or under defence contracts, very little is known about it outside. In due course, however, there is little doubt that polymers based on inorganic materials such as phosphorus, oxygen, nitrogen, boron, chlorine, etc., will become available with properties so different in degree as to be different in kind from the existing materials, and, in particular, we may expect tremendously increased heat resistance from them.

Perhaps, however, the most important line of advance in the last few years has been much less obvious and much more subtle. True, it began before 1955 and it has not led to the discovery of any new materials, but it has led to the control of the physical form in which existing materials are made available. Plastics materials are generally supplied as powders or liquids, but sometimes it is desirable to have them available in the form of rods or sheets or tubes or films or foils. This is an obvious example of the control of physical form but another more profound and more important is the control of the size, shape and porosity of powder particles. It is this kind of control that has now been achieved. This may not, on the face of it, seem to be very important, but the suitability of a plastic for a given purpose is governed not only by the fitness of its physical properties for the particular end-use, but by the fitness of the material in a particular physical form for a particular fabrication process.

Polyvinyl chloride provides us with some excellent examples. To make a cable covering by extrusion from a plasticized composition it is conventional to mix the polymer with plasticiser, stabiliser, lubricant, etc., and it is desirable to achieve the complete mixing and combination of polymer and plasticiser as quickly as possible. Careful examination has shown that the best form of polyvinyl chloride for this purpose is a fine powder which has the largest available surface area and a reasonably low packing density. Fig. 4 is a micro-photograph of such a polymer. On the other hand, to coat fabric with a layer of plasticised p.v.c. to manufacture the well-known leathercloth the material is required to mix with plasticiser without absorbing it until the mixture is heated to the gelation temperature and to give a paste-like premix of polymer, plasticiser, pigment and so on. This paste must have the property of thinning-out satisfactorily under the shearing action of a scraper blade (which regulates the thickness of the coating applied to the fabric) and yet it must not be sufficiently 'runny' to penetrate through the fabric or to run off the edges and all over the equipment. It has been found that these requirements can be met with basically the same chemical, polyvinyl chloride of a given molecular weight and given molecular weight distribution, but with the particle structure shown in the electron microscope photograph, Fig. 5. The size, size distribution and shape of the particles are strictly controlled and—in contrast to the particles seen in Fig. 4—the particles are non-porous.

Just how important this kind of control is to the development of the plastics industry may be judged by the fact that one company in this country at the end of the war offered two forms of vinyl chloride polymer, one made by the emulsion technique and



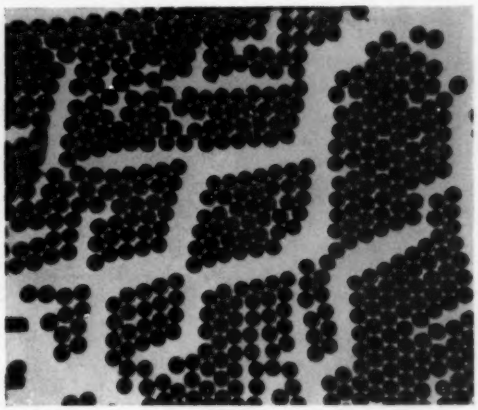


Fig. 4 (left). Micro-photograph of a vinyl chloride polymer of large surface area and low packing density. (Magnification approx. ×100.) Fig. 5 (right). Electron microscope photograph of a vinyl chloride polymer suitable for paste making. (The distance between the two rectangular markers in the bottom left-hand corner is one micron.)

the other by the granular technique. Today, this same company makes no less than fifteen kinds of polymer excluding co-polymers, and these fifteen materials differ one from another not only in their molecular weight and molecular weight distribution, but in the size, shape and size distribution of their particles.

A much more spectacular development which has occurred in the last five years or so has been the result of work carried out by Professor Ziegler in Germany and Professor Natta in Italy. It has led to the ability to control the course of the polymerization much more precisely when making the big molecules of plastics, to dictate the orientation of particular groups or atoms which recur along the chain and even to achieve polymerizations that hitherto have been impossible. This kind of control is known as 'stereospecific polymerization' and its results are illustrated in Fig. 6. It will be seen from this figure that in the atactic form of the polymer the pendant groups are arranged in a random manner on either side of what we may describe as the axis of the molecule. In the isotactic form of the polymer however the pendant groups will be seen to be arranged all on one side of this axis, and in the syndiotactic form the pendant groups occur alternately on either side of the axis.

Although these discoveries are very recent there has already flowed from them one development of outstanding practical importance. This is the appearance on the market of polypropylene. Propylene is a gas obtained from the cracking of petroleum and which until five years ago was an unwanted by-product. It was known that propylene could be polymerized, but under the old hit-or-miss methods of polymerization the products were atactic and completely useless as plastics. However, propylene can be polymerized into an isotactic form to produce a material very similar in many respects to the well-known polythene but with much greater stiffness and a much higher melting point. No longer is propylene burnt in the disposal chimneys of oil refineries.

Another aspect of this kind of work has been to eliminate yet another uncontrolled factor from our polymers. It was for long believed that if one took a gas such as ethylene, and polymerized it under the appropriate conditions, all that happened was that the ethylene molecules joined one another end to end and formed very long chains without any side branches. However, continuing research and examination of polythene revealed that in fact accidents happen every so often, and a long polythene chain would suddenly sprout a side branch. Most of these branches are fairly short and occur on average about every hundred carbon atoms along the chain. It was not thought that they had any great significance, until, as a result of these newer methods of polymerization, new forms of polythene were produced which were much stiffer, much more brittle and had higher softening points than the conventional forms. It was then discovered that these new forms of polythene had far fewer branches and this low degree of branching which leads to closer packing together of the chains, with an accompanying increase in density of the material, is responsible for the changes in physical properties.

So far, this review has covered the development of new formulations, the control of physical form and the control of some aspects of the geometry of poly-

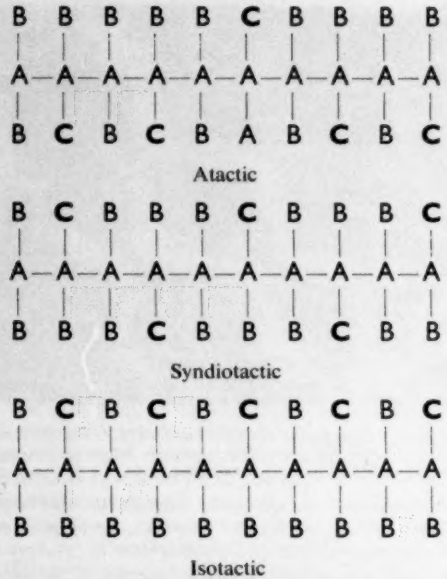


Fig. 6. Stereospecific polymerization: control of orientation of side groups (C) in atactic, syndiotactic and isotactic polymers.

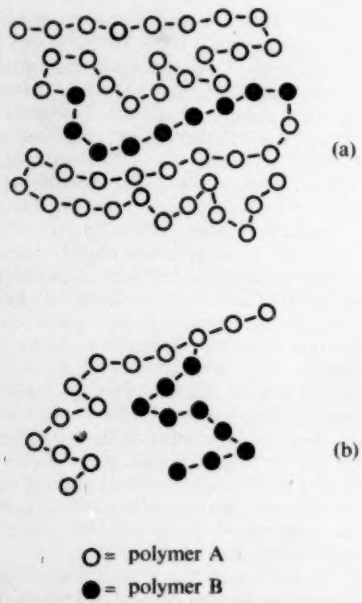


Fig. 7. Representation of (a) *block and* (b) *graft copolymers.*

mer molecules. There are two other developments of the control of the geometry which should be briefly mentioned. Reference has already been made to the classical random method of co-polymerization, and it was then stressed that this method gave no control over the order in which the starting monomers (such as vinyl chloride and vinyl acetate) joined the molecule. The two new developments do give some control over this factor.

In the so-called 'block co-polymers' (Fig. 7a) it is possible to form a molecule in which different segments along the length of the chain are composed wholly of one of the two components. The second development is called 'graft copolymerization'. Here a ready-formed polymer molecule (e.g. a rubber molecule) can have a second, different polymer molecule (e.g. polymethyl methacrylate) grown on to it as a branch (Fig. 7b).

Both block and graft co-polymers have properties different not only from those of the individual polymers but also from those of the random co-polymers. It is too early to give many examples of the practical application of these developments but already they have been used to improve the ageing characteristics of rubbers and the dye-acceptance of fibres and films, and there is little doubt that in the future it will be found that they have opened yet another chapter in the story of polymers.

There is one other aspect in the development of materials which is worthy of mention and that is the physical mixture of polymers with one another to achieve specific effects. Here there is a situation somewhat similar to that in metals where desirable properties can be obtained by alloying one metal with another. Interesting products have been made by mixing, blending or 'alloying' two or more plastics with one another and at the present time particular interest is centred on blends or 'alloys' notable for exceptionally high resistance to impact.

Although it is perhaps not strictly a development in polymers it may be permissible to include here a reference to the uses of high energy—atomic—radiations in the plastics industry. There are two interesting possibilities. Neither has yet progressed very far and time alone will enable us to judge the value of high energy radiation to the plastics industry. In the first place it is possible to initiate polymerization processes by high energy radiation and so avoid the necessities for the use of catalysts which can—and do—contaminate the final product, and for building special plants to operate at high temperatures and high pressures. Secondly, high energy radiation can be applied to the final polymers. In general two effects take place simultaneously, the one being to cross-link the polymer and thus increase its strength, stiffness and heat resistance, and the other being to

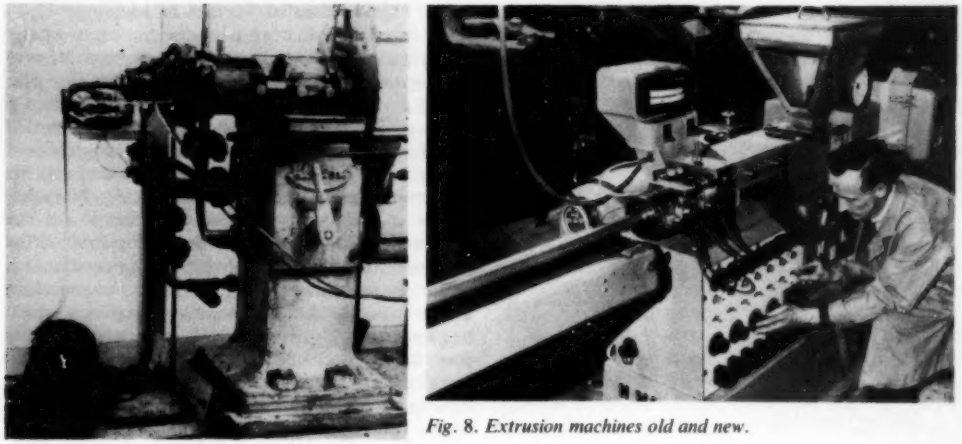


Fig. 8. Extrusion machines old and new.

degrade the material and thus worsen all its properties. Most often the degradation reaction occurs to a greater extent and faster than the cross-linking reaction, but there is one interesting exception and that is polythene. There, lightly cross-linked materials can be made which have outstanding resistance to high temperatures.

Developments in Processes

Reference has alryead beenmade to the fact that the advent of cellulose acetate introduced the injection moulding process into plastics technology as a practicable proposition and to the fact that this process is only a modification of a process borrowed from metallurgy. Looking over the other standard processes of the plastics industry we find that compression moulding used with the thermosetting materials was borrowed lock, stock and barrel from the rubber industry, and so was the whole of the technology of fabricating p.v.c. in its plasticised forms. Thus, open roll mills or internal mixers developed for the rubber industry, modified simply by the addition of extra heating, have been used to mix vinyl polymer, plasticisers, stabiliser, pigment, filler, etc., just as they have been used for over a hundred years to compound rubber mixes. Equally, the calender used since Victorian times for making rubber sheets and films requires little more than extra heating in order to make it suitable for making p.v.c. sheet. If an extruder for polythene, nylon, p.v.c. or polymethyl methacrylate bears little external resemblance to the old rubber forcer used by our grandfathers (Fig. 8) a glance at an engineering drawing shows that fundamentally it differs only in detailed refinements—many of them again concerned with increased heating power—and in greater attention to external design and finish.

However, in the last few years considerable work has been done on the fundamental physics and engineering of the various processes which it must be confessed have, up to the present, been used by a rule of thumb art. From this work has come the realization that the crux of satisfactory plastics production lies in adequate and uniform heating of the material. This has been a great step forward and has led to faster, more efficient and therefore cheaper production.

It is not possible here to review in detail the improvements which have taken place in the whole field of plastics fabrication and one example must suffice. Twenty years ago extruders built to handle rubber were being used to extrude polythene and p.v.c. Today, however, machines are designed to handle a particular plastic material and are even refined to the extent of being designed to do one particular job only, such as making film, covering a cable or extruding lighting fittings. Much thought has been given to the proper design of the screws and there are screws of different length to diameter ratio, of different shape of thread, of multi-start design, of uniform pitch with decreasing depth, of uniform depth and decreasing pitch, of sudden change of cross-section and so forth (Fig. 9). The design of the torpedo, which serves to spread the material within the machine and to ensure even heating—and if cable is being made to carry the wire, or if a tube is being made, to make the hole in it—is the subject of detailed study, as are the streamlining of all the internal cavities and the precise proportions and design of all the various parts of the die.

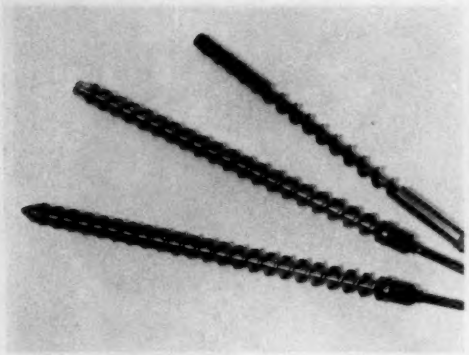


Fig. 9. Typical screws for extruding (top) nylon, (middle) p.v.c., (bottom) polythene.

It is interesting to consider the scope of the screw extruder in the plastics industry. It was originally used to produce endless lengths of profiled shapes such as tubes, draught excluders and car wing piping, and to cover wire. Shortly after the war the extruder was used as a means of filling very large moulds to make a limited number of mouldings of very great size in the fabrication of which there were special difficulties concerned with the contraction of the plastic on cooling from the molten state when it filled the mould to the solid state when it was extracted from the mould. The special technique of 'extrusion moulding' as it was called was found to be a satisfactory way of overcoming the specific difficulties encountered. Later, when plastic bottles made their appearance, the extruder was again used to make a tube which is nipped within the mould and blown against the mould walls to take up the appropriate shape, using the torpedo of the extruder to introduce the air into the tube. Extrusion machines are used to make tubular film and also wide sheet film of varying thicknesses. They can be used to coat paper, hessian and other fabrics with plastics. Extrusion machines are used to mix plastics with other materials to give homogeneous compounds and screws working inside cylinders are used instead of rams on some types of injection moulding machines. In other words, in recent years the extruder has undertaken jobs previously done by injection moulding machines, by calenders, by spreading machines, by casting machines, by open roll mills and by internal mixers, and indeed it can be said that today the extruder can do pretty well anything that any other plastics fabricating machine can do—except possibly shape thermoplastic rigid sheets.

Applications of Plastics to Lighting

So far we have been concerned almost wholly with plastics as materials and with methods of processing them and very little with the articles produced from them. This is perhaps inevitable in a paper prepared by a chemist, but as the members of this Society are interested in the use of plastics it would be a faint-hearted chemist who declined the challenge to say something on this subject. Nonetheless it should be emphasized that this is not the proper province of the chemist but is that of the engineer, whose responsibility it is to understand his materials and to appreciate both how to use them and how not to use them—an understanding which has not been conspicuously evident in the past. However, the engineers are learning; they no longer treat plastics as if they were metals or glass and they have come to recognize that plastics are to be used where—and only where—they can make an effective technical and economic contribution by doing a job better, or cheaper, or better and cheaper than it has been done before.

Ten years or more ago lighting engineers recognized that the strength and toughness of acrylic sheet would permit the large enclosures called for by fluorescent lamps to be made in one piece and that the mechanical properties of the material were such as to remove risk of serious harm should breakage accidentally occur. If memory serves rightly, one of the earliest uses by lighting engineers of this thermoplastic sheet was in the fabrication of covers for the very first fluorescent street lighting lanterns, and as members of this Society look upon many of our towns and cities of today they must feel some satisfaction at the way in which this early experiment has prospered. Whether of course their artistic friends would agree with them appears from the Press to be a matter of some doubt.

It must have been the lighting engineers' well-known interest in producing small numbers of special lighting fittings which led them to appreciate that this could be readily achieved with a material which shaped so easily and which involved only small tool costs. A little later, they exploited the good machining properties of acrylic sheet in the manufacture of lenses and refractor plates, and so further widened the use of this material for street lighting purposes. It is worthy of note that many of the pioneer lanterns developed so long ago are still by no means outmoded, and that the fears which many must have had regarding the weathering characteristics of this new-fangled material have proved groundless. And so—sometimes—are the efforts of pioneers rewarded.

One of the properties of acrylic sheet which engineers were inclined to use too widely in those long ago days was the readiness with which sections

could be cemented together. Plastics technologists tried—with some success—to teach that it was better to make a shaping in one piece than to stick a number of pieces together. This general principle is true but it has to be said that ease of cementing remains a valuable property of acrylic sheet, and has been rightly used—for example, to attach lettering to the diffusing enclosures of railway platform lighting fittings. By this means has been brought to pass what only a short time ago most of us would have thought to be impossible—when we travel on our railway system by night we can see where we are. The most spectacular use of cemented constructions is of course in illuminated signs, where colour can be used with effect which—it is to be hoped—will never be allowed to degenerate into vulgarity. The production of these cements for acrylic and other plastics is part of the plastics story, but their development lies outside the scope of this paper.

The use of thermoplastic sheet appears to have suited many of the lighting requirements of this country very well, and indeed it is probably true to say that at the present moment it still does. But changes are on the way which illustrate some of the general trends mentioned earlier in the paper.

If the previous order of treatment be reversed to take new processes first, we observe that today we are injection moulding and extruding many acrylic components which yesterday were shaped from sheet. What is perhaps of particular interest in these developments is that the processes can be carried out using the fine powder-like acrylic polymer—which is another example of the developments arising from the control of physical form. Until recently, to injection mould or to extrude an acrylic component, acrylic granules had to be used. These are rather like over-sized granulated sugar and are produced by processing the polymer powder. This processing not only involves a further expense but tends to degrade the material so that the advances in processing technique can be claimed with justice to have led not only to a cheaper material but to a better material.

One of the interesting developments in extrusion which will be known to some is that of extruding the polymer through a circular die to give a cylinder which is then slit by a knife and post-formed to produce almost any outline desired. A very recent and as yet incomplete development is that of embossing the extrusion as it is made. By this means it is hoped that a much wider range of patterns will be available, and indeed it seems that it will be possible to impress different patterns on different sections of a fitting should this be required.

While talking about the use of extrusion techniques it is interesting to note that they have enabled one of the oldest plastics—cellulose acetate—previously thought to be unsuitable for general lighting applications—to find a new lease of life. Mention has already been made of the dimensional instability of cellulose acetate which can cause large flat areas of the material to distort in atmospheres of varying humidity. However, when the material is extruded as a narrow tube which is then coiled round a former of the required shape and the coils are cemented together, fittings are obtained which are both remarkably attractive and stable in operation.

It is of course true that such advances in processing techniques are not spectacular but they are very important for they are leading—and leading rapidly—to greater variety and lower cost.

Nonetheless, it is the advances in materials which will be of most interest to lighting engineers. The two most serious limitations of plastics up to the present have been those of relatively low stiffness and of relatively low resistance to elevated temperatures. Today, we are witnessing the birth of materials with greater stiffness and higher softening points. The two most likely to affect the practice of lighting engineers within the next few years are polypropylene and the polycarbonates. Both of these materials are marked by temperature resistance well in excess of that of the materials used in lighting up to now.

Polypropylene is not a transparent material except when it is in the form of a thin film. It is a lightly translucent material which can, if necessary, be pigmented to give a range of opals. It may well be wondered whether, in these days of fluorescent lighting, the better temperature resistance that polypropylene offers over established plastics matters enough to warrant a change-over. May a chemist make two comments? The first is that not all lighting is fluorescent lighting—for which those of us who still have some regard for the pleasantness of our homes are more than grateful. The second is that high temperature resistance is not the only virtue of polypropylene. It is very light and very tough, qualities which must interest lighting engineers.

The second group of materials—the polycarbonates—can be produced as transparent materials of considerable strength, and as such they must be carefully studied by lighting engineers.

Perhaps a word of warning is not out of place. These are early days for these materials and we still have much to learn about their properties and limitations and any enthusiasm must be suitably tempered with caution.

In concluding this review, may a question be asked of lighting engineers? It has been said that the only purpose of the steel in a reflector fitting is to hold up a coat of paint. Up to the present lighting engineers have used plastics as sheets, as mouldings and as extrusions. One of the most important developments

in plastics is the growth of plastics films—cellulosic, polythene, vinyl, polyester, polypropylene and others. But apart from a limited use of fairly thick vinyl material—foils rather than films—the lighting engineer seems as yet to have made no use of plastic films. Why?

Discussion

MR F. WIDNALL: Dr Child, in the early part of his lecture made some reference to the Lord Mayor's show; if he was correct in saying he thought he was the dust cart after the carriage, then I feel very much like the dust. The subject of his paper is extensive and relatively new to illuminating engineers. The first difficulty I find is coping with the long names the chemist uses in his everyday vocabulary. 'Perspex' we can understand and we use regularly, but the more complex names baffle us.

On the application of plastics to our industry, a lot of work has been done with 'Perspex' in the last few years. In our development, so often, as in one case demonstrated, they tend to misfire rather than click, and it takes time for the materials supplied by the chemist to become practical for the engineer.

Turning to the application of new materials, one point is that we have borrowed from normal press-work and extrusion techniques in applying many plastic materials; but I do not know of any corresponding technique applicable to plastic films. I think they will find applications, for instance, the reflecting film might be applied to optical control systems, and where decorative effects are required, the configuration of films might well be followed up.

I would like to ask Dr Child whether he forsees any possibility of a better control of the translucent and diffusing properties of plastic materials while the other properties are maintained as they are today. We could use materials with better controlled diffusing characteristics. It is true that in the normal manufacture of lighting fittings it takes a long time to absorb the new materials. With plastics it takes a long time to finding the catches. You are told the advantages but it is only with time that the snags emerge. It does present the engineer with a real difficulty. There is a high risk element and I would like to know what progress we can expect in getting more accelerated tests which are reliable on the application of plastics. Many of us will remember that when we first started using 'Perspex' we applied paint to achieve an opal appearance, and it was a long time before we found that the combination did not behave as was expected. You may remember that in the case of street lamps which were installed practically all the world over, the reaction in some tropical countries was not what was expected. There is a great field for reliable testing methods for any of these plastics.

MR. S. ANDERSON: I would like to ask two questions. The first is concerned with the now very familiar property of certain detergent washing powders to make our white laundry 'whiter than white'; it is possible to do something of this nature with opal 'Perspex' to give us an even better apparent reflection factor than the plain white material does? The second is concerned with the radiation technique for improving the stability or strength of polythene. Is this applicable to other plastics besides polythene, and is it a technique which could be applied to an article after it has been formed, or is it only applicable to the basic material before forming?

MR A. G. SMITH: Amongst the properties given in the opening paragraphs of the paper, such as low specific gravity and low thermal conductivity, I think a further one might well have been included, i.e. high thermal expansion. This property has unfortunate results when one endeavours to link-up large plastic components of a lighting fitting with a metal backbone having a very much lower thermal expansion. Even more difficult is the problem of overcoming distortion in the plastic component itself arising from temperature gradients and the high thermal expansion. These occur not only in the drop from moulding to room temperatures but also over the operating range of temperatures due to heat dissipated in the fitting.

It would seem that, to gain better dimensional stability, a plastic which has cold workability with a degree of rigidity is desirable, whilst as a general rule one would prefer thermoplastics to soften at higher temperatures and have much lower co-efficients of expansion.

Another property which has not been mentioned is that of springiness. I remember reading in an American plastics journal something about a material used for making small components which had some of the characteristics of a spring. There are many applications in lighting fittings for what one might call the bits and pieces which hold parts together; available metals fall short of the total requirements. A stainless steel spring, if adequately non-corrosive, tends to be much softer than a carbon steel spring, whilst the latter is difficult to protect from corrosion. What is wanted is a homogeneous material which is resistive to corrosion but does not fall short of true springiness. Such properties do not appear to be very far removed from those of some plastics already available in this country.

MR G. K. LAMBERT: I hope Dr Child will not

think me unfair in springing a very difficult question: he is probably one of the few people who can help. We have used 'Perspex' or 'Diakon' for over fourteen years now, for transparent enclosures to street lanterns. We know that normally there is no trouble due to discolouration. Occasionally however, we increase lamp wattage, or make some change in lantern design and discolouration occurs within 200 to 300 hours. Can Dr Child say anything regarding the mechanism of this discolouration and how it can be avoided, particularly for the clear 'Diakon'?

MR J. H. MORRISON: I would like to ask a question of Dr Child with regard to the demonstration of applying acids to plastics. We use a lot of polythene insulated cables and on two or three occasions we have had faults, and found that the p.v.c. has been actually burned away. It has burnt right through and the manufacturers have said this has been due to cinders being used on the footpath and the sulphuric acid from the cinders has had this effect on the material. Either the manufacturers have told us an untruth or the insulation is of inferior manufacture.

MR K. J. GODDARD: I should be glad if Dr Child could tell us if anything is being done about the building up of static changes in plastics.

MR D. H. HOLLOWAY: Regarding the metallic film exhibited during the course of the lecture, I have understood that the metallizing of solid sheets of plastic has not been altogether satisfactory mainly because of the lack of adhesion between the two similar materials. How would the metal film stand up to constant use inside a lighting fitting at a temperature of say 50°C?

The second question concerns polythene films. This being a rather specialized question I do not expect a detailed answer, but I would be interested to know whether the transmission of the polythene film to radiant energy at 2537 AU would remain constant or whether the radiation would cause degradation of the material and subsequent loss in transmission.

MR J. B. HARRIS: Dr Child says at the end of the paper that lighting engineers have made no use of plastic films. I don't think this is exactly true, as lighting engineers have certainly begun to make use of plastic films in luminous ceilings.

One important characteristic of materials used in public buildings is concerned with their ability to support combustion. In the London County Council area there are fire regulations which, in some instances, would prohibit the use of certain plastics.

Although the p.v.c. film ceiling has many advantages, it has one drawback as it exists today, and that is its poor concealing power when used with artificial light sources. Could we have further information on other p.v.c. films which might be available for use today. P.v.c. films are easily maintained as they are stretched over light weight mild steel supporting frames and as light diffusers they are cheap and easy to install.

MR B. C. OSSITT: Would Dr Child please tell us the best way of cleaning 'Perspex' fittings.

MR R. J. FOTHERGILL: It seems to me that the development of the use of these plastics represents a large amount of team work. What happens in practice? Does the chemist who has discovered the material report to the chemical company's sales organization who then approach persons who might use the material? Is the only way of finding out what is available to approach the sales organization?

I have here a simple little prototype diffuser. I can stand on it and it will remain intact but if I drop a 1 lb. weight on it from a height of five feet very likely a star fracture will occur. Is there any work going on which will explain the mechanism of the occurrence of these fractures so that we may hope for this acrylic material to have greater impact resistance in the future?

Surely films are not used by the lighting industry because they are not self supporting.

DR W. E. HARPER: As most of you here will know, I have to exist as an engineer among a convolution of chemists of whom Dr Child is one. But Dr Child is not only a chemist—he holds office in the Plastics Institute and that prompts a suggestion I would like to make. While listening to Dr Child I could not help feeling that we technologists keep ourselves far too much in water-tight compartments and only on occasions such as this do we learn of what our colleagues in other fields of technology are doing. I would like to suggest to our own Papers Committee that they approach sister societies such as the Plastics Institute to see whether it is possible to arrange a day's symposium when we could meet and discuss informally our common interests. I should be glad to have Dr Child's reaction to this suggestion.

MR A. RIMMER: As a representative of one of the firms who are the back-bone of the Society of Glass Technology, I agree with what Dr Harper has just said on co-operation. We tend to sit in our own little cubicles and state our own ideas on these problems at great expense and the knitting together of

our activities is very loose. Regarding the paper, I was astonished that Dr Child had come thinking this is a lighting engineers' conference; it is the Summer Meeting of the Illuminating Engineering Society. There has been no mention, for instance, of the transmission of daylight by transparent materials such as FRP sheeting. I feel that this sort of data has been sadly lacking, but work is now going on on the transmission properties of such partially diffusing materials. Could Dr Child tell us where to get this information for transparent plastics.

THE AUTHOR (in reply): In introducing the discussion Mr Widnall touched on a subject dear to my heart in referring to the chemical names of plastics. I am quite sure that this is a very real difficulty in the way of gaining general acceptance of plastics materials by engineers and the general public, and that it would pay the plastics industry handsomely if it had short simple words like 'brass', 'lead' and 'steel'. The Americans have given us one such acceptable word—'nylon'—which is short, euphonious, meaningless and easily pronounced in all the major languages. We in Britain tried to help by inventing the word 'polythene' as a generic name, but the Americans with their gift for shortening words like 'lift' to 'elevator' have succeeded in shortening 'polythene' to 'polyethylene'. Trade marks, when they are short and simple—such as 'Perspex'—tend to be used as generic names, but this usage is to be deprecated from all points of view, and it is to be hoped that before too long some more words like 'nylon' will be introduced as generic names for the other types of plastics.

Mr Widnall also referred to the lack of techniques which can be borrowed from other industries and applied to the use of films in lighting. I would like to make a plea here. It is that we should not always slavishly copy what somebody else has done with some different material, but that we should give some honest thought to the best way to employ the properties of the material that we wish to use.

Mr Widnall asked about the possibility of better control of the translucency and diffusion of plastics materials. Work to improve the properties of plastics in various ways goes on without cease, and I am sure that the answer to Mr Widnall's question is that indeed these optical properties will be improved as time goes on, but of course I cannot say anything about the rate at which this improvement will occur as discoveries can still not be made to order.

Mr Widnall raised the question of accelerated tests. The plastics industry is asked over and over again by all sorts of users to provide reliable information quickly, and we are constantly asked to employ accelerated tests. We are so far from a *full* understanding of the origin and nature of the properties of plastics that at the present time we cannot honestly place any reliance on any kind of accelerated test, because we do not know what factors we are magnifying and what factors we are suppressing in such a test. It is true that, in order to comply with certain specifications, various kinds of accelerated tests are carried out with plastics and the results of these tests are quoted, but these tests are all arbitrary and it is often possible, by changing from one arbitrary test to another, to invert an order of merit between different samples—which goes to show how unreliable such tests in fact are. Indeed one might go so far as to say that at the present time many accelerated tests are meaningless.

Mr Anderson asked a question about the effect of high energy radiation on plastics. The answer is that polythene is the only material which has shown any advantage as a result of exposure to high energy radiation. Even with polythene, unless the conditions of exposure are carefully controlled the result can be to degrade the material, but with all other plastics the degradation effect proceeds very much faster than any improvement. Because the effect of high energy radiation on polythene leads to cross-linking of one polythene molecule to another, and so reduces the ability of the material to melt and flow, the treatment has to be applied to the finished article. It would be impossible to shape the material if it were cross-linked first.

In reply to Mr A. G. Smith I cannot pretend that in a talk of this length I have mentioned all the advantages or all the disadvantages of plastics, and it is indeed true that I did not mention the high coefficients of thermal expansion of plastics materials. They all have high coefficients of expansion relative to those of metals, but here again intelligent design, which takes account of this fact, can usually, if not always, obviate any resultant difficulties.

While we are seeing the birth of thermoplastics with higher softening temperatures, I do not think we shall be able to do anything about their high coefficients of expansion for years.

With regard to Mr Smith's query about springiness, I must confess that I cannot quite understand what he is getting at. Quite a number of plastics have a measure of resilience and a considerable resistance to fatigue in flexure and vibration. Some plastics have, for instance, been used to form integral hinges in such things as spectacle cases, and in this application use is made of a measure of resilience of the plastics, but I cannot see any plastics at the moment replacing a steel spring in heavy engineering.

Mr Lambert asked for information about the mechanism of discolouration in acrylic materials. Fully polymerized polymethyl methacrylate shows

very little tendency to discolour on exposure, but commercially available material may contain traces of materials used to assist polymerization and these are frequently materials which develop a yellow colour on oxidation. Furthermore, commercially available material sometimes contains unpolymerized methyl methacrylate monomer which again can be oxidized to give yellow products. It should, however, be said that very few materials commercially used in industry show anything like as good resistance to ageing and discolouration as does the bulk of the commercially available polymethyl methacrylate.

Mr Morrison referred to the 'burning' of p.v.c. sheaths over polythene insulated cables buried under cinders. I am quite sure that the p.v.c. itself will withstand sulphuric acid without disintegrating, but it must be remembered that the composition based on p.v.c. used for sheathing the cable contains heat stabilizers, lubricants, pigments, possibly filler, and certainly one or more plasticizers and perhaps extenders. When talking about the resistance of plasticized p.v.c. to chemical attack one therefore has to consider the possibility of attack on all these other ingredients as well. This is a point which is often overlooked with all sorts of plastics and it must be borne in mind.

Mr Goddard has raised the question of static charges on plastics. It is a sad fact that a virtue in one respect is often a handicap in another. Plastics are all good to excellent electrical insulants with high volume resistivity and high surface resistivity. This fact is responsible for their very widespread use as insulants in all kinds of electrical equipment, but it does mean that they will readily develop static charges on their surfaces when they are subject to any kind of friction or relative movement, and that these static charges are unable to leak away across the surface or through the body of the material, with the result that the charges become bigger and bigger and can cause more and more embarrassment. There is one way only in which this drawback can be overcome and that is by reducing the insulating qualities of the plastics. This can be done in one of two ways—either by incorporating an antistatic agent (in effect a soap or detergent) in the plastic material during its manufacture, or by putting a layer of such an antistatic material on the surface of the finished articles. Both lines of approach have been tried, and with both a measure of success has been obtained in some instances, but no wholly satisfactory answer has been obtained as yet. Work, however, continues on this problem.

It is indeed true, as Mr Holloway suggests, that the adhesion of metallic films on to plastics is by no means perfect, but the degree of adhesion obtained in commercial practice is sufficient for many purposes. Depending upon the kind of metal that has been employed, I think that some metallized films would be found to be satisfactory in lighting fittings at temperatures of 50°C.

With regard to the transmission of u.v. light by polythene film, there will be some absorption of the light by the polythene and, in the presence of oxygen, this will lead to deterioration of the film and further decrease in transmission. The film may discolour and will become progressively more brittle.

Mr Harris accidentally brought up a difficulty of definition within the plastics industry. Three terms are commonly used in the plastics industry to describe materials available in the physical form of large flat areas of relatively small thicknesses. These are 'sheet', 'film' and 'foil', and it must be admitted that there is no clear-cut, generally agreed, distinction between films, foils and sheets. In this paper, I have used the word 'film' to mean thin, very flexible materials, whereas I personally would class as a 'foil' the p.v.c. material used at present for some luminous ceilings. However, without quibbling about the meanings of words I will agree that this is a development along the lines on which I was thinking.

The question of fire risk is a terribly complicated one, and it is quite true that the regulations of some authorities, such as the LCC, preclude the use of certain kinds of plastics. Unfortunately, the fire risk arising from the use of plastics is not something that can be decided unambiguously, and various tests have been devised and used from time to time, and discarded when somebody has changed his opinion as to the value of the test. I appreciate that the subject is one of tremendous importance and not one to be dismissed lightly. At the same time, I sometimes am forced to wonder whether the tests employed, and the regulations drafted on the basis of these tests, are always strictly relevant to the risks really involved.

With regard to the concealing power of p.v.c. for luminous ceilings, I cannot say more than that this again is one of the many problems on which the industry is working.

In reply to Mr Ossitt, the best way of cleaning acrylic fittings is to use soap and water—or detergent and water—with a soft cloth or mop.

Mr Fothergill has raised the question of the impact resistance of plastics. The impact strength of plastics is a very complicated property. In the past, various people have devised arbitrary tests (which have usually been named after their inventors) and these tests are often used in specifications for plastics, but, like the accelerated tests about which we have already spoken, they suffer from severe limitations. At this moment, some fundamental work is being undertaken in various laboratories throughout the

world to elucidate this very complex problem and as a result of this we hope that it will be possible to devise measurements of the strength of plastics which will mean something. At the present time, I am quite sure that there is only one test which it is worth carrying out to see whether a proposed article will stand up to the service conditions required—that is to make the article, put it in service and see if it stands up.

Mr Fothergill suggests that films are not used in lighting because they are not self-supporting. Many a lighting fitting I have seen has employed a tremendous amount of metal purely and simply for the purpose of holding some glass or vitreous enamel or other material in place, so I do not think that this is a wholly valid objection to the use of films.

I am most interested in Dr Harper's suggestion and I can assure you that the Plastics Institute also will be extremely interested in this suggestion. I will make it my business to draw their attention to it at once, and I have no doubt that before very long your Secretary will be hearing from Mr J. N. Ratcliffe, the Secretary of the Plastics Institute, to see how we can start the ball rolling.

Mr Rimmer asks for the source of information about optical and other properties of plastics. I am sure that at the present time the best way to obtain this information rapidly is to enquire from the suppliers of the raw materials. I think that, without exception, they examine thoroughly all the relevant properties of their products and are very ready to distribute this information. There is one difficulty in this procedure, and that is that where more than one material can be considered for a job a number of raw material suppliers has to be asked for information, and then the enquirer himself has to make a comparison of the different materials on the basis of the information he has been given. Unfortunately, there is no central research institute or authority which at the present time can undertake to provide an unbiased comparison on different plastics materials for any given purpose.

UDC 535.241

A Note on Quantities of Light

By J. G. HOLMES, A.R.C.S., B.Sc. (*Fellow*)

Summary

Some of the terms used in lighting design calculations for the components of flux in an interior and their ratios are described. Suggestions are made for some new terms and symbols, and for a more practical meaning for 'light output ratio'.

(1) Introduction

In recent discussions on the utilization of light and particularly on lighting design, it became necessary to clarify certain concepts used in the calculations of the quantities of light flux inter-reflected within a room. The light is emitted by the lamps, controlled by the lighting fittings and directed on to the ceiling, walls and working plane. The discussions have covered three aspects of this process, namely the fraction of the lamp flux which reaches the working plane to provide useful light for the task, the interchange of flux between surfaces, and the brightness distribution of the fittings and of the surroundings; this note deals with the first of these, and other papers[6, 7] deal with the other aspects.

Particularly, the calculation of the utilized flux has been examined in detail by the Lighting Design Data Panel of the Technical Committee, which has issued an interim report[1] and which has now prepared a full Technical Report[2] on the calculation of utilization factor. The terminology used in these calculations and the various components of flux in its passage from the lamps to the working plane are the subject of this note, and it is suggested that the terms in this note should be generally adopted.

Names, symbols and simple arithmetical relations are given for the components of the flux. The diagram accompanying this note illustrates some of the terms and the relations between them. The terms are described in reference to the whole installation and the surrounding surfaces, but some of them can relate equally well to a single lamp and a single fitting.

(2) Proposed Terminology

(2.1) The flux output from lighting fittings

LAMP FLUX ϕ

The total flux emitted from all the light sources in the installation.

The manuscript of this paper was received on November 30, 1960.

FITTING FLUX F

The total flux emitted from all the lighting fittings in the installation. This comprises the upward flux and the downward flux.

UPWARD FLUX F'

The flux emitted from the fittings in directions above the horizontal. (The upper hemispherical flux.)

DOWNWARD FLUX F''

The flux emitted from the fittings in directions below the horizontal. (The lower hemispherical flux.)

LIGHT OUTPUT RATIO η

The ratio of the fitting flux to the lamp flux. For the measurement of a single fitting, if the light output of the lamp itself varies with temperature or for some other reason when it is enclosed in the lighting fitting, the value of the lamp flux used in this ratio should be that emitted by the lamp alone in the normal temperature and operating conditions. The Light Output Ratio will then include the effect of temperature, etc., on the lamp, as well as the effect of absorption of light in the fitting.

UPWARD LIGHT OUTPUT RATIO η'

The ratio of upward flux to the lamp flux.

DOWNWARD LIGHT OUTPUT RATIO η''

The ratio of the downward flux to the lamp flux.

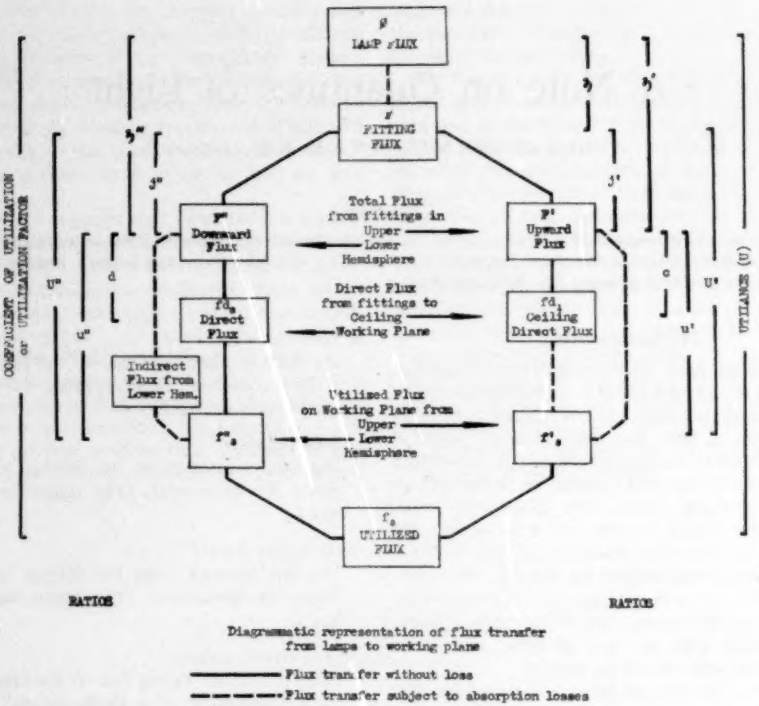
UPPER FLUX FRACTION j'

The ratio of the upward flux to the fitting flux. This is also the proportion of the fitting flux which is emitted in the upper hemisphere.

LOWER FLUX FRACTION j''

The ratio of the downward flux to the fitting flux. This is also the proportion of the fitting flux which is emitted in the lower hemisphere.

These last five terms are usually regarded as pro-


LAMP FLUX
FITTING FLUX
Total Flux from fittings in Upper Lower Hemisphere
Direct Flux from fittings to Ceiling Working Plane
Indirect Flux from Lower Hem.
Utilised Flux on Working Plane from Upper Lower hemisphere
UTILIZED FLUX
Downward Flux
Upward Flux
Direct Flux
Ceiling Direct Flux
COEFFICIENT OF UTILIZATION or UTILIZATION FACTOR
RATIOS
RATIOS
Diagrammatic representation of flux transfer from lamps to working plane
Flux transfer without loss
Flux transfer subject to absorption losses

perties of a lighting fitting rather than of an installation. The relations between these terms are as follows:

$$F=F'+F''$$
$$\eta=F/\phi$$
$$\eta'=F'/\phi$$
$$\eta''=F''/\phi$$
$$\eta=\eta'+\eta''$$
$$j'=F'/F=\eta'/\eta$$
$$j''=F''/F=\eta''/\eta$$
$$j'+j''=1$$

(2.2) The components of flux in an interior

These terms generally relate to the whole installation rather than to single fittings.

DIRECT CEILING FLUX fd_1
The flux incident on the ceiling direct from the lighting fittings.

DIRECT WALL FLUX fd_2
The flux incident on the walls direct from the lighting fittings.

DIRECT FLUX fd_3
The flux incident on the working plane directly from the lighting fittings.
The suffix $_3$ relates to light incident on the working plane.

UTILIZED FLUX f_3
The total flux which reaches the working plane, either directly or after reflection.

UTILIZED UPWARD FLUX f_3'
The part of the upward flux which reaches the working plane, after reflection.

UTILIZED DOWNWARD FLUX f_3''
The part of the downward flux which reaches the working plane, either directly or after reflection.

The relations between these terms are largely dependent on the dimensions and reflecting properties of the whole interior. The reports of the Lighting Design Data Panel deal with them in detail using

some of the terms given in the next section, but the following may be noted:

$$F=fd_1+fd_2+fd_3$$
$$f_3=f_3'+f_3''$$

(2.3) Flux ratios in an interior

These terms relate to the whole installation, and are not generally applicable to single fittings.

CEILING RATIO c

The ratio of the direct ceiling flux to the upward flux. This is also the proportion of the upper hemispherical flux which reaches the ceiling directly.

$$c=fd_1/F'$$

DIRECT RATIO d

The ratio of the direct flux to the downward flux. This is also the proportion of the lower hemispherical flux which reaches the working plane directly.

$$d=fd_3/F''$$

UPPER FLUX UTILANCE u'

The ratio of the utilized upward flux to the upward flux. This is also the proportion of the upper hemispherical flux which reaches the working plane after reflection.

$$u'=f_3'/F'$$

LOWER FLUX UTILANCE u''

The ratio of the utilized downward flux to the downward flux. This is also the proportion of the lower hemispherical flux which reaches the working plane, either directly or after reflection.

$$u''=f_3''F''$$

UPWARD UTILANCE U'

The ratio of the utilized upward flux to the fitting flux.

$$U'=f_3'/F=j'.u'$$

DOWNWARD UTILANCE U''

The ratio of the utilized downward flux to the fitting flux.

$$U''=f_3''/F=j''.u''$$

UTILANCE U

The ratio of the utilized flux to the fitting flux. This is one of the basic concepts in the design of most lighting systems, and it is in a sense the measure of the effect of the surroundings on the utilization of the light emitted by the installation of lighting fittings. It is the ratio of the total flux reaching the working plane to the total flux emitted by the lighting fittings.

$$U=f_3/F=U'+U''=j'.u'+j''.u''$$

In the familiar calculations of Coefficient of Utilization, based on the work of Harrison and Anderson,[3] the illumination on the working plane has been related to the total light emitted by the lamps and not directly to that emitted by the complete fittings. The same basis was used in the more recent work of Jones and Neidhart[4] and in the interim report of the Lighting Design Data Panel.[1] The appropriate terms are as follows:

UPWARD COEFFICIENT

The ratio of the utilized upward flux to the lamp flux. This is the ratio of that part of the upper hemispherical flux which reaches the working plane, after reflection, to the total flux emitted by the light sources.

$$\text{Upward coefficient}=f_3'/\phi=\eta'.u'$$

DOWNWARD COEFFICIENT

The ratio of the utilized downward flux to the lamp flux. This is the ratio of that part of the lower hemispherical flux which reaches the working plane, either directly or after reflection, to the total flux emitted by the light sources.

$$\text{Downward coefficient}=f_3''/\phi=\eta''.u''$$

COEFFICIENT OF UTILIZATION

The ratio of the utilized flux to the lamp flux. The official term given in British Standard 233:1953 is Utilization Factor, rather than Coefficient of Utilization, and it may be noted that this very important ratio is truly a factor used in multiplication, rather than a coefficient. However, the American usage seems to favour 'Coefficient of Utilization' and this term has been used in the Technical Report.[2] No symbol has been agreed for this term.

$$\text{Coefficient of utilization}=f_3/\phi=\eta.U=\eta'.u'+\eta''.u''$$

(3) The Usefulness of 'Utilance'

The utilance for a lighting installation in an interior is related to the total light output of the lighting fittings rather than of the lamps, and it is therefore equally applicable to reflector-bulb lamps, luminous ceilings or ordinary suspended fittings. The idea of using utilance was approved by the International Commission on Illumination[5] at Zurich in 1955, but it has not yet come into general use.

One important feature in the calculation of utilance is that it is dependent on the *shape* of the polar curve of a lighting fitting and not the absolute values of the intensity. It is therefore relatively easy to estimate the utilance in any interior by reference to standardized calculations on polar curves of similar shape to that for the fitting under consideration. The three figures required are the lower flux utilance (u'') and

the upper flux utilance (u'), which are determined by the shapes of the lower and upper halves of the polar curve and the properties of the interior, and the lower flux fraction (j''), which is a property of the lighting fitting only and is also determined by the shape of the polar curve; the utilance is then given by the simple formula:

$$U = j''u'' + u'.(1 - j'')$$

The utilization factor (or coefficient of utilization) is the product of utilance and the light output ratio of the particular fitting ($\eta.U$).

(4) Acknowledgments

The proposals made in this note are those of the author, whose thanks are due to Mr W. Robinson for clearly stating the problem in the Interim Report, to Mr J. M. Waldram for the idea which led to the diagram, and to Mr R. G. Horner, the chairman of the BSI Committee on Lighting Terminology.

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[6] Hopkinson, R. G. 'Indices of Glare Discomfort', *Trans. Illum. Eng. Soc.* (*London*), **25,** 135 (1960).
[7] Report on Nomenclature and Symbols for Radiation Transfer Calculations. (To be published.)

I.E.S. Gold Medal

To mark the occasion of the Society's Golden Jubilee, Council instituted the award of the I.E.S. Gold Medal.

The regulations governing the award are as follows:—

(1) The Medal shall be bestowed for outstanding contributions to the advancement of lighting.
(2) The Medal shall be awarded at intervals of not less than two years.
(3) Recipients of the Medal may be persons of any nationality and may or may not be members of The Illuminating Engineering Society.
(4) Nominations for the award may be made by any member of the Society in writing and in confidence to the Honorary Secretary. Nominations shall be considered by a Panel appointed by the Council and the Panel's recommendations shall be submitted to the Council by the President.

The first award was made in 1959. Nominations for the next award should reach the Honorary Secretary not later than March 1, 1961. They should include a concise statement of the outstanding contributions of the nominee.

I.E.S. Monograph No. 3

The New Approach to Interreflections

The third in the new series of I.E.S. Monographs has just been published and includes the contribution entitled 'The New Approach to Interreflections' by R. O. Phillips and S. J. Prokhovnik of the School of Architecture and of Mathematics respectively of the University of New South Wales.

This monograph discusses the principles involved in determining the effects of interreflections by the solution of a set of simultaneous linear equations. The method depends on the determination of the flux transferred from any one finite surface to any other within the room, and the establishment of the required 'form factors' is considered in some detail. The application of the method to a number of situations is indicated, including the determination of the apparent reflectance of cavities. Differences between this method and that of Moon and Spencer are discussed, both theoretically and by comparison with experimentally determined values. In general it is shown that the methods of calculation here described give results which agree very well with measurement. An appendix describes how the equations can be rapidly set up and solved by matrix algebra and a digital computer.

Copies of the Monograph can be obtained from the Secretary, The I.E.S., 32 Victoria Street, London, SW1, price 5*s*., by post 5*s*. 6*d*.

Annual General Meeting

Notice is hereby given that the Annual General Meeting of The Illuminating Engineering Society will be held at 5.15 p.m. on Tuesday, May 9, 1961, at the Federation of British Industries, 21 Tothill Street, London, S.W.1, at which the following business will be brought before the meeting:—

(1) To receive the Report of the Council and the Accounts for the year ending December 31, 1960.
(2) To elect Officers and Members of Council.
(3) To fix the remuneration of the Auditors.

Additions to the List of Members

Diploma Membership

The Council has accepted the application for the Society's Diploma in Lighting Engineering from the following, who is now a Diploma Member:

K. E. Parsons

New Members

The following applicants have been duly elected by the Council to Membership of the Society:

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Representative: D. S. Wade

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Shepherd, R. W.	3 Benton Hall Walk, Cochrane Park, Newcastle upon Tyne, 7.
Shihab, A. A.	I.W.A./242, Bab El-Baidth, El-Fokani, Mosul, Iraq.
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Woodward, E.	175 Prospect Road, Totley, Sheffield.
Worrall, E. J.	1 Clent Gardens, Lydiate, near Liverpool.

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